psi per foot of depth for this area in calculating the pressure resistance in the unplugged dry holes. That is the pressure at the bottom of a mid-filled hole of 5,000' depth (2385 psi or .477 psi per foot) would exceed the natural piezometric head (2335 psi at 5,000' or .467 psi per foot) in the area by 50 psi or by approximately 107' of salt water head. This is a very low pressure tolerance since as can be expected, an unsupported earthen well bore will slough and heave with time and the likely pressure resistance to repressuring below may be as high as .2 or .3 psi per foot. The use of a tolerance of .01 psi per foot is an arbitrary rule of thumb, but a better criteria for evaluating such situations does not presently exist.

The problem of creating excessive or dangerous pressure conditions due to waste disposal underground may be approached from a different perspective. Understandably, the injection of waste fluids into a fault block area would necessarily increase the aquifer pressure but variation in injection techniques can be utilized to control the magnitude of pressure buildup. Should a certain aquifer intended for waste confinement be considered unsafe beyond a given pressure buildup toleranc then alternating aquifer zones might be utilized to permit pressure leak off and pressure subsidence below the maximum pressure condition. Where the aquifer properties are known then the rate of pressure subsidence ca be calculated and the shutdown time determined in order to maintain a safe pressure condition. On the other hand, with the advent of recent water desalting processes an industrial plant might furnish its water supply requirements from a brackish water aquifer with desalting applied to create the desired water quality. Waste waters from the same plant would then be returned to this aquifer at a considerable distance an cycling process would thus furnish both the need for plant water supply while simultaneously preventing undesired pressure buildup in the zone of waste confinement. The use of this concept would depend on the supply volume required by an individual plant, the water quality required, and the cost of the desalting process necessary to accomplish this.

As can be seen from Figure 23 there is no correlation between the volume of the fault block aquifer into which injection occurs and the corresponding pressure buildup resulting from injection. The regional geology should be carefully studied to determine the fault block area and degree of confinement in order to anticipate the magnitude of future piezometric increases. This study revealed that with increasing depth the geologic structures become more complex and the formation transmissibility is less; thus it would be expected that higher injection pressures will be required as deeper injection zones are utilized. Below 5,000', the problem is magnified by the cost of special non-corrosive steels which are required to reach these depths. A good summary of the problems arising from well construction is reported by Klotzman (2) in an unpublished paper.

The Texas Water Quality Board, Subsurface Disposal Section, is responsible for reviewing permit applications and determining the feasibility for underground disposal. Further, they are charged with recommending to the Board the denial of a permit request for subsurface disposal in those areas considered inappropriate.

It was discovered from this study that an investigation of geologic structure on a regional basis yields a far more realistic and accurate picture of the proposed disposal zone than in an area radiating only two to three miles from the proposed injector. This comparison is shown in Figure 5, a structure map on the Basal Miocene interval. Many structural details which would be revealed by a regional study of the geology are missing from an area encompassing only a two to three mile radius, (dashed circle, Figures 2 and 5). This radius of study is more than ample to properly define and consider the container in which waste fluids will be placed. The waste fluids will displace nearly all of the original salt water near the injector and the distance which the waste fluids would migrate is very small compared to a three mile radius. The pressure effects due to injection, however, cannot be considered in such a short radius and it is this consideration which demands a larger study area. In this study, a "regional" area is considered as that area of 10 miles or more on a side which is required to define the original depositional conditions, plus those subsequent conditions in which deformation occurred. Where an original depositional gradient of a formation is exhibited, such as 140' per mile for the Frio, a sudden interruption in the gradient over a regional area would indicate deformation by faulting, by folding or by the upthrust movement of salt dome intrusion. Interpretations such as this cannot be accomplished in a three mile area of investigation. Without proper study a disposal well considered in communicatic with other disposal areas may actually be separated by sealing faults which prevent hydrologic fluid communication.

Earthquakes are caused when opposing earth stresses become unequal and a balancing effect occurs. It seems logical to conclude that any subsurface pressure increase in the magnitude of 300 to 400 psi would not trigger an earth movement. Pressure differentials of far greater magnitude have been created in this area previously, due to productio[n] from oil and gas fields and to injection of oil field brines, without injurious effect. The cause and effect of earthquake occurrences due to waste injection in the area remains for detailed investigation. These sediments are plastic in nature and no basement rocks are present. Van Pollen and Hoover (18) give an excellent discussion on the mode of occurrence of an earthquake. It appears that considerably higher pressure buildups must be experienced from injection before the occurrence of earth shock is imminent. Oil field waste disposal experience over the last 40 years has caused no major earth movements. The maximum permitte[d] pressure buildup in the Houston Industrial Area will first be limited by the dry holes which exist and secondly by the geological limitations of the zone into which subsurface disposal is planned. The geological [lim]itations would include the size of the aquifer as compared to the volume of fluid which it must confine, the thickness of impervious shales separating the disposal zone from structurally higher zones containing usabl[e] water and the separation of the disposal zone laterally from any fresh water interface.

CONCLUSIONS

1. The magnitude of pressure buildup due to injection in the Houston Industrial Area does not now present any predictable danger to the fresh water sands of the area. Such a danger might be envisioned from leakage along existing fault planes which extend from the depth of injection to the fresh water horizon. Judging from the pressure differentials already created from oil and gas field production and from brine disposal in the area, the magnitude of pressure buildup will be far below the necessary pressures to overcome existing earth stresses.

2. Many dry holes exist in the Houston-Galveston area which penetrate the desirable zones for waste disposal. In addition some of these holes lack sufficient surface casing or were inadequately plugged so as to protect the fresh water sands. Where these holes exist, the Texas Water Quality Board will guard against excessive pressure buildup in limiting the permissible pressure tolerance increase ($\sim$ .01 psi/foot of depth).

3. Unfortunately, the problem of pressure buildup due to injection is not a function of the sand thickness only, but is determined by the degree of confinement of the aquifer into which injection occurs. Very large pressure increases may result from injection into very thick sands even though the area appears to be infinite in extent. This would occur if the area were confined by faulting or sand pinchout. Conversely, a thin sand interval may experience little pressure buildup due to its unobstructed and large areal extent.

4. The actual migration of disposed waste fluids extends a relatively small distance from the source of injection since these fluids effectively displace the original brine fluids of the aquifer in a radial area around the injector. In contrast, the depositing of this waste volume near the injector creates a pressure interference which is felt over a far greater area.

5. Due to the plastic nature of the Gulf Coast sediments and to the lack of basement rocks in the area, it does not appear that earth shocks would be caused by the pressure buildup effect of waste disposal.

6. Wherever there is concern for excessive pressure buildup due to injection, the pressure may be controlled by alternating the zone into which disposal occurs or by cycling the water supply-disposal horizon.

RECOMMENDATIONS

(1) The presence of regionally placed pressure-monitoring wells will permit the intelligent use of the area sediments for disposal. As applications for injection are made, the strategic location of such wells can be determined. In the absence of plugging of known dry holes, monitor wells should be required between the dry hole and the area of injection, just as the Celanese Chemical Co. has provided at Clear Lake, Texas.

(2) Continuous pressure recording and volume recording meters for each injector are necessary to determine the accuracy of subsurface pressure calculations. A periodic check of all measuring devices would prove their reliability. Periodic (bottom-hole) pressure fall-off tests would provide pressure data in the aquifer.

(3) Applicants for future permits should be required to furnish accurate regional geology not limited to a short radius from the proposed injector. All controlling geologic features should be presented.

(4) An inventory of the prospective disposal sands and their classification as to volume and pressure capacity is essential. Such inventory should be made for each stratigraphic area exhibiting hydrologic communication. Such an inventory could be combined with a study of future disposal requirements to provide intelligent future planning.

(5) The determination of the rate of outflow (leak rate) from each hydrologic province would permit the scheduling of the shut-down time required to reduce the pressure in a given area to an acceptable

level. Conversely, such knowledge would permit an injection rate to be maintained at such volume that no excessive pressures are created. Injectors completed at other depth intervals would be alternated in disposing the fluid waste. The pressure falloff-buildup rate can be ascertained by computer computations such as demonstrated here.

(6) Special research should be made on the phenomena of fracture induction and leakage along old fault planes as related to injection operations. Additional research would include a study on the cause and effect of earthquakes as related to injection.

(7) Field and laboratory tests should be made to determine the compatability, rate of deterioration, and adsorption rate of certain wastes under the subsurface conditions of pressure and temperature.

(8) Consideration should be made for a cyclic disposal-water supply program in which water desalting processes may provide usable water supply to the plant while simultaneously providing pressure relief to the zone of disposal.

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APPENDIX

Definition of Terms

1. AF - Exact number of required image wells
2. ANGLEF - Angle of fault wedge, degrees
3. BLINE - Length of leaking fault line or space line, feet
4. DP - Depth of penetration, feet
5. F - Outflow factor
6. FT - Fault throw, feet
7. IA - Counter for designating contributing line
8. ICE - Fault block number or area number
9. J - Image well number
10. JD - Monitor point number
11. JJ - Number of real injector
12. K3 - Counter for elapsed time period, days
13. MN - Number of transfer image wells along an individual line (500' increments)
14. N - Total number of calculated image wells plus real well for each fault wedge (or line)
15. NP - Fault line number
16. PR - Incremental increase (or decrease) in piezometric head from real or image well, feet
17. QA - Outflow across individual line
18. QC - Cumulative injection - this injector, gallons
19. QD - Incremental difference in rate of recharge or discharge, gpm
20. QP - Injection rate of partial penetrating well, gpm

21. QT - Cumulative injection - all injectors- this block, gallons

22. RI - Image well reduction factor

23. SM - Slope of fault line or space line

24. ST - Sand thickness, feet

25. SUM - Algebraic sum of PR values at each monitor point location, JD

26. SUMT - Total pressure buildup at monitor point, feet

27. SUMPRS - Pressure buildup contribution from adjacent fault blocks, feet

28. T - Number of days since injection began to time of pressure determination

29. TR - Fault transmissibility

30. TS - Average transmissibility of sand in fault block, gallons/day/foot

31. WHP - Wellhead pressure @ monitor point, JD

VITA

William Henry Price was born in Paris, Texas on October 31, 1927, the son of Lucie Clift Price and Pinckney Bryan Price. His public education was received entirely in the State of Texas with a high school diploma awarded at Austin High School, Austin, Texas in January, 1945. After service in the U. S. Army, he received a Bachelor of Science in Petroleum Engineering, January, 1951 at the University of Texas. He was employed by the Interstate Construction Co., Pine Bluff, Arkansas and became Field Superintendent in charge of asphalt paving. In 1954, he was employed by the Lion Oil Co., El Dorado, Arkansas and became District Petroleum Engineer, Kansas-Oklahoma District. In 1957 he began consulting work in petroleum engineering with Mr. Joe Ballanfonte in Austin, Texas and in 1960, until the present, has continued as an independent Consulting Petroleum Engineer. He is a Registered Professional (Petroleum) Engineer in the State of Texas and a member of the Society of Petroleum Engineers, American Institute of Mining, Metalurgical and Petroleum Engineers, Inc. and a member of the Texas Society of Professional Engineers. He began his graduate studies leading to this research paper in September, 1967.

Permanent address: 2408 Bridle Path
Austin, Texas

This thesis was typed by Yvonne G. Darilek

APPENDIX 4-6

Appendix 4-6

Area of Review Determination Review of Artificial Penetrations
(Texas Water Commission, 1977)

REVIEW OF ARTIFICIAL PENETRATIONS

Improperly plugged or completed wells which penetrate the injection zone pose a serious constraint to injection operations. The determination of what constitutes an improperly completed or plugged well is a difficult problem. Among the many variables are geology, completion methods, plugging methods, expected reservoir conditions, etc.

There are several schools of thought concerning the radius of investigation for artificial penetrations. This Agency has used as a rule of thumb, a 2 1/2-mile radius. This is not an absolute requirement. The distance can be adjusted as the circumstances require. For example, after making Reservoir pressure calculations, it may be determined that a 3-mile review is required because of a large pressure increase at 2 1/2 miles. On the other hand, low volumes in a thick reservoir may result in a insignificant pressure at 1 mile. However, later requests for volume increases can result in a second record search. In order to maintain a uniform approach to the radius of review, all applicants should submit data for 2 1/2-miles with the application. Additional data can be submitted if needed after an evaluation is made.

Generally speaking, dry holes on the Texas Gulf Coast were abandoned without long string casing left in the hole. Surface casing was generally set and cemented at the base of fresh water and no long string was set. A plug is normally set at the base of the surface casing and at the top. The hole and the casing between plugs is usually filled with drilling muds. Due to the unconsolidated nature of the Gulf Coast Sediments and the plastic nature of most tertiary shales, abandoned well bores probably do not remain open for long periods of time.

In the west and north central part of the State, injection zones, confining beds and most of the overburdened strata are competent, indurated rocks. Well bores remain open for indefinite periods of time, and frequently drilling fluids and cement may not be in the well bore because of lost circulation zones.

A well which has been properly abandoned is one where interformational transfer of fluids does not occur or will not occur as a result of injection. Although our primary concern is protection of groundwater resources, oil or gas formations, or other mineral bearing zones may be affected, i.e., magnesium is produced from the Yates Formation and other commercial brines probably exist in the State.

Probably the greatest danger from artificial penetrations occurs in the West Texas area. Most reports of flowing abandoned wells or ground-water contamination from oil field brines is from this area. There are several possible causes for this, but it is primarily the result of well bores, which do not collapse around casing or do not close after casing is removed, or the fact that lost circulation zones are common and the hole may be unintentionally abandoned or completed without adequate mud or cement. Another problem common to all areas of the State is some wells are temporarily abandoned with casing in the hole and then forgotten.

Often the information submitted with an application is inadequate, incomplete or in error. For example, many tabulations indicate that the well is a producing well, however, the well may not have produced in many years and is temporarily abandoned. In order to check the status, the Railroad Commission records must be reviewed. Form W-10, semi-annual well status reports and Rule 14B(2) (plugging) exceptions are two methods of establishing well status. Additionally, the "Well Schedule" is a computer print-out of all active wells and is updated monthly. There are separate schedules for oil and gas and are filed by district.

Additionally, all of the penetration in the area may not be tabulated or listed by the applicant. The General Land Office maintains up-to-date records on oil and gas well locations as does the Railroad Commission. The RRC also maintains reproducable field maps which have generally been updated within the past year.

After all the data has been assimilated, a determination must be made is a hazard exists. Using all the data available, some conflicting conclusions can be made. There are no unique solutions to the problems and a value judgment may be required.

There are several rules of thumb which can be applied. None are absolute and the reviewer should use individual knowledge and experience to supplement these ideas.

(1) In the Texas Gulf Coast area, the bore holes normally do not remain open for a long period of time. The weight of the drilling fluid (if the hole remains open) or the collapsed sediments should prevent any upward migration of native fluids if reservoir pressures are not significantly increased. A rule of thumb has been a pressure increase of 15 psi/1,000 feet of depth. This is based on the pressure differential of a 9.5 lb. mud. normal Gulf Coast reservoir pressures, and a considerable safety factor.

(2) In West Texas area, uncemented well bores can result in vertical avenues of escape. Generally, wells which penetrate the injection zone should have cement across the injection interval to prevent corrosion, casing failure and escape of fluids of contamination of produced fluids.

(3) It is not uncommon to find wells which have been abandoned with long string casing still in the hole and the well has not been plugged. Therefore, if no information concerning the well can be found, we should proceed as if it is not plugged and has long string casing in the hole. This is probably one of the most dangerous situations which can exist.

In summary, artificial penetrations, which are through the confining beds is one of the most serious problems in any injection operation. Each application for a well must be thoroughly evaluated in terms of reservoir pressure increase and artificial penetration in the area.

In order to review the surrounding penetration and to determine if a hazard exists, an accurate picture of the well and well status is necessary.

APPENDIX 4-7

Appendix 4-7

Investigation of Artificial Penetrations in the Vicinity of Subsurface Disposal Wells (Johnston and Greene, 1979)

NOTICE

The following report titled "Investigation of Artificial Penetrations in the Vicinity of Subsurface Disposal Wells" is a draft of an in-house report and as such it represents an unfinished on-going project. The Texas Department of Water Resources requests that the report not be reproduced for general distribution and that it be used by the U.S.EPA only for the purpose of reviewing the Department's proposed Underground Injection Control Program.

INVESTIGATION OF ARTIFICIAL PENETRATIONS IN THE VICINITY OF SUBSURFACE DISPOSAL WELLS

Technical Report

By

Orville Johnston, P.E. and

Charles J. Greene, Geologist

Texas Department of Water Resources

1979

ABSTRACT

The distance to which artificial penetrations should be reviewed in the vicinity of an injection well is dependent upon many variables including the hydrologic and geologic characteristics of the disposal zone, wastewater properties, injection rates and volumes, amount of separation between the base of fresh water and disposal zone, and other disposal operations utilizing the same interval. The Texas Department of Water Resources uses a 2½-mile radius of investigation as a rule of thumb for evaluating applications for waste disposal well permits; however, this distance can be adjusted if reservoir pressure resulting from well injection calculated using the nonequilibrium formula developed by Theis (1935) warrants. Recommendations to reenter and plug abandoned wells were made when pressure calculations indicated injection well operation might create a hazard in improperly plugged wells.

One method of establishing a uniform radius of investigation is the evaluation of disposal zone models. The models demonstrate the sensitivity of the radius of investigation to changes in different reservoir, fluid and injection variables. Since evaluations of artificial penetrations are made prior to drilling a disposal well, it is sometimes difficult to obtain accurate data for the variables affecting reservoir pressure. The investigation of a 2½-mile radius should be continued unless prior justification of a smaller radius is supported by reliable reservoir data. Injection operations should be reevaluated using the data obtained from reservoir testing after well completion.

INTRODUCTION

The Texas Department of Water Resources (TDWR) is the permitting agency for underground injection of industrial wastewater in Texas. One of the aspects of evaluating the suitability of a subsurface disposal project is the investigation of artificial penetrations in the vicinity of a proposed injection well. The distance to which abandoned or completed wells should be reviewed depends upon may variables, including the hydrologic and geologic characteristics of the disposal zone, wastewater properties, injection rate and volumes, amount of separation between base of fresh water and disposal zone, and other disposal operations utilizing the same interval.

The TDWR uses a 2½-mile radius of investigation as a rule of thumb. If reservoir pressure calculations indicate a significant pressure increase at 2½-miles, it may be determined that a greater area of review is necessary. Initially, all applicants must submit data on all known penetrations within a 2½-mile radius of investigation, unless prior justification for a smaller area of review is made. Additional data can be required if the reservoir pressure calculations warrant.

The determination of what constitutes an improperly completed plugged well is a difficult problem. Generally, a well that has been properly completed or abandoned is one where interformational transfer of fluids does not occur or will not occur as a result of changes in the reservoir pressure. Although our primary concern is protection of groundwater resources, oil and gas formations and other mineral bearing zones (i.e., magnesium produced from brines in the Yates Formation) should be protected.

The evaluation of a well must consider the regional geology, completion or plugging methods, and expected reservoir conditions. Most dry exploratory (oil wells) holes on the coastal plain were abandoned with surface casting set and cemented at the base of fresh water and long string casting was usually pulled. Cement plugs were set at the base of the surface casing and at the surface with drilling mud left in the hole in most wells. Due to the unconsolidated nature of the sediments and the plastic nature of most Tertiary shales, abandoned well bores probably do not remain open for long periods of time; however, for the technical evaluations of aquifer penetrations, the holes are assumed to remain open.

In the west and north-central part of the State injection zones, confining beds and most of the overburden strata are more competent, indurated rocks. Well bores will remain open for indefinite periods of time, and frequently drilling fluids and cement may not be in the well bore because of lost circulation zones.

Probably the greatest danger from artificial penetrations occurs in the West Texas area. Most reports of flowing abandoned wells or groundwater contamination from oil field brines are from this area. There are several possible causes for these problems including well bores that do not collapse around the casing or close after casing is removed, or lost circulation zones that force operators to unintentionally abandon or complete a well without adequate mud or cement.

Another problem common to all areas of the State is wells that are temporarily abandoned with casing in the hole and then forgotten. Often erroneous data is submitted on plugging or completion reports. For example, many tabulations indicate that a well is producing; however, the well may not have produced in may years and is temporarily abandoned.

METHOD OF EVALUATION

The staff evaluation of artificial penetrations primarily consists of review of the completion and/or plugging records in the subject area to identify improperly completed or abandoned wells. The pressure increase caused by the proposed injection program is calculated for each potential problem well using estimated values for transmissivity and storage in the nonequilibrium formula developed by Theis (1935). Multiple well and image well effects are considered where applicable. The nonequilibrium formula in United States Geological Survey units is expressed as:

$$\Delta h = \frac{114.6Q}{T} \int_{\frac{1.87r^2 S}{Tt}}^{\infty} \frac{e^{-u}}{u} \, du$$

Where:

$U = \frac{1.87r^2 S}{Tt}$

Δh = change in head at observation point (feet)
Q = discharge of well (gallons per minute)
T = transmissivity (gallons per day per foot)
r = distance to observation point (feet)
S = storage coefficient (dimensionless)
t = time (days)

The nonequilibrium formula is based on the following assumptions:

1) the aquifer is homogeneous and isotropic
2) the aquifer is of infinite areal extent and constant thickness
3) the discharging (injecting) well has a small diameter and completely penetrates the aquifer
4) water is released instantaneously from storage

Although no aquifer exists in nature that meets all of these assumptions, the nonequilibrium formula can be applied successfully to estimate pressure changes. The nonequilibrium formula was modified by Wenzel (1942) as follows:

$$\Delta h = \frac{114.6Q}{T} W(u)$$

Where W (u) represents the "well function of u" and other terms are as previously defined.

$$\int_{\frac{1.87r^2 S}{Tt}}^{\infty} \frac{e^{-u}}{u} = W(u) = -0.577216 = \log_e u + u \frac{u^2}{2.2!} - + \frac{u^3}{3.3!} - \frac{u^4}{4.4!}$$

Values for W (u) for values of u from 10^{-15} to 9.9 were tabulated by Wenzel (1942).

The formula for obtaining u, as previously stated, is:

$$u = \frac{1.87r^2 S}{Tt}$$

To solve the above equations and estimate pressure increases (Δh), the storage coefficient must be determined. The storage coefficient is the volume of water that is released or taken into storage per unit surface area of an aquifer per unit change in the component of head, normal to that surface. The formula for the coefficient of storage is:

$$S = f(w)\, \emptyset\, m \left(B + \frac{a}{\emptyset}\right)$$ (modified after Jacob (1950))

Where

- f(w) = weight of 1 cubic inch of formation water at stated temperature (pounds)
- Ø = porosity
- m = thickness of saturated aquifer (inches)
- a = 1/bulk modulus of compression of aquifer skeleton (square inches per pound)
- B = 1/bulk modulus of compression of aquifer water (square inches per pound)

REVIEW OF WASTE DISPOSAL WELL FILES

A review of TDWR Staff Technical Reports written during the evaluation of Industrial Waste Disposal Well Applications Nos. WDW-33 through WDW-151 was conducted to determine the distances from injection wells at which improperly abandoned or completed wells have previously posed a hazard to freshwater resources. The scope of this review is limited to those wells described in the Technical Reports as potential problems. An evaluation of the artificial penetrations in the vicinity of many of the earlier permitted wells should be made using real values for reservoir conditions and pressures resulting from many years of injection.

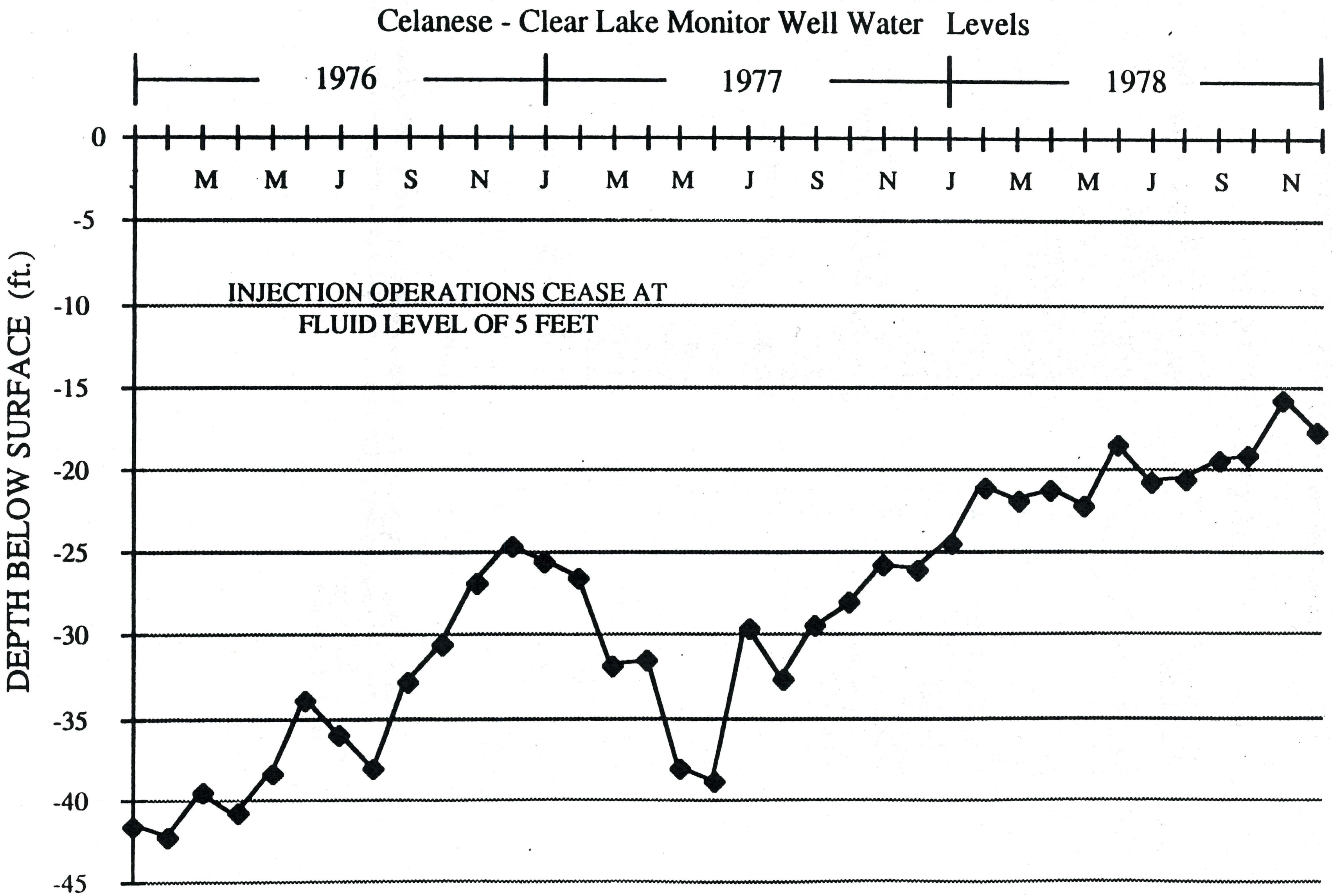
Recommendations to reenter and plug an improperly plugged well or to install a monitor well were made when the calculated increase in pressure at a potential problem well was predicted to be sufficient to cause fluids to migrate up the well bore of the problem well from the injection zone to the base of freshwater. If pressure calculations indicated that the injection well operation would not result in a significant increase in pressure at an improperly plugged well, plugging or monitoring was not recommended.

If pressure calculations indicated a potential hazard where plugging was not practicable, a pressure monitor well was installed and a provision in the permit required the permittee to cease injection operations and recomplete in another zone or plug and abandon the disposal well when reservoir pressures approached a critical level as indicated by the pressure in the monitor well. This approach was taken with Celanese Chemical Company's disposal wells which are located near the Clear Lake Oil Field where twenty producing wells were completed with insufficient surface casing. A graph of the pressure increase since 1976 is shown in Figure 1.

Of the files on 91 waste disposal wells reviewed, 39 Technical Reports described a total of 58 wells considered to be potential problems (not counting the 20 producing wells with insufficient surface casing near Celanese Chemical Company). Plugging or monitoring was recommended in the Technical Reports for 25 improperly completed or abandoned wells at distances ranging from 250 to 16,400 feet from the injection well. Calculations of pressure increase indicated that the injection operations would not create a hazard in 33 of the potential problem wells evaluated at distances ranging from 2,800 feet to 14,500 feet. These figures are listed in Table 1 and represented graphically in Figure 2.

This review suggests that no standard radius of investigation of artificial penetrations can be applicable to all proposed subsurface disposal projects. The distance from an artificial penetration to the injection well is only one of many variables controlling the pressure increase as a result of injection operations. For example, a recommendation to plug or monitor an unplugged well 16,400 feet from a proposed injection well in Harris County was made due to an injection rate of 1,650 gpm (WDW-89 and WDW-90) with nearby injection wells utilizing or permitted to utilize the same interval (Ethyl Corp. Permit No. WDW-86 @ 1000 gpm). Conversely, pressure calculations indicated no hazard for an unplugged well 2,800 feet from a proposed injection well in Nueces County (WDW-97 and WDW-98) based on an injection rate of 250 gpm with no other injection wells utilizing the same interval. Discussion of the relative significance of the variables affecting pressure increase is necessary to determine the distance from a proposed injection well at which artificial penetrations should be evaluated.

Figure 1



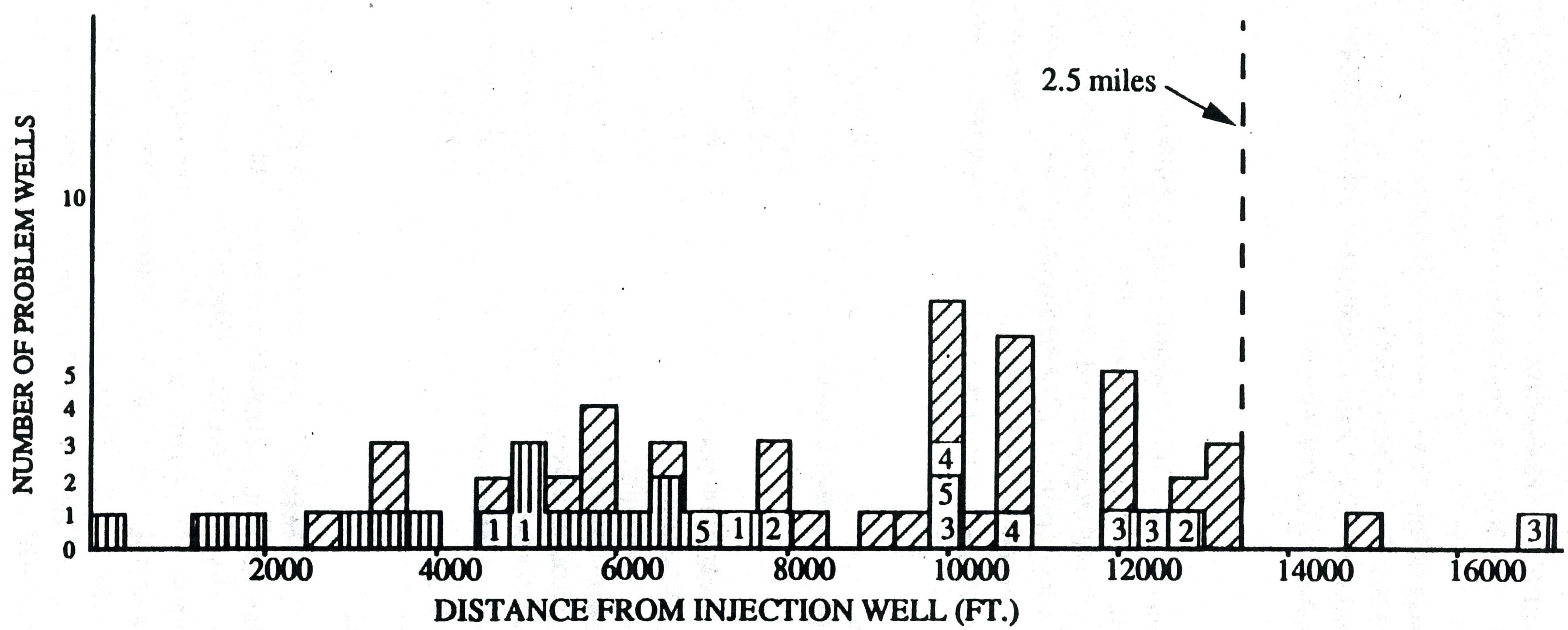
Celanese - Clear Lake Monitor Well Water Levels
1976
1977
1978
M M J S N J M M J S N J M M J S N
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
DEPTH BELOW SURFACE (ft.)
INJECTION OPERATIONS CEASE AT FLUID LEVEL OF 5 FEET

Table 1. Evaluation of Petential Problem Well Recommendations
Waste Disposal Well Permit Nos. WDW-33 to WDW-151

WDW No.	No. of Wells	Distance (feet)	Recommendation
33, 45, 69*	20	7,920 to 13,200	monitor
34,113,114	4	10,200, 13,200 & 2 @ 12,000	Δρ calc no hazard
51	2	10,000, 10,560	Δρ calc no hazard
59, 71, 99		10,000, 10,560	plug or monitor
49	1	12,000	Δρ calc no hazard
70	2	11,800, 12,500	Δρ calc no hazard
73	2	5,400, 7,800	Δρ calc no hazard
78	2	3,000, 4,000	plug or monitor
78	3	5,900 to 6,000	Δρ calc no hazard
80, 127, 128	1	10,800	no hazard
80, 127, 128	1	12,700	plug
82, 83	1	8,000	Δρ calc no hazard
82, 83	1	4,900	plug or monitor
86**	4	1,900, 4,500, 5,000, 7,280	plug or monitor
89 & 90***		10,000, 12,000, 12,400, 16,400	plug or monitor
89 & 90	1	14,500	Δρ calc no hazard
91	1	7,920	plug or monitor
92	1	250	plug
97, 98	5	2,800, 6,700, 13,000 & 2 @ 13,200	Δρ calc no hazard
103	1	9,000	Δρ calc no hazard
105	1	9,500	Δρ calc no hazard
110	2	10,000	Δρ calc no hazard
111	2	3,300	Δρ calc no hazard
119	1	10,500	Δρ calc no hazard
123, 124	1	3,600	plug or monitor
126	2	@ 10,500	Δρ calc no hazard
130	4	5,800, 6,500, 6,900 & 9,900	plug or monitor
133	1	1,320	plug or monitor
139	3	4,800, 2 @ 10,000	Δρ calc no hazard
140	1	5,000	plug or monitor
141	2	5,500, 6,500	plug or monitor

* Celanese Chemical Co. disposal wells are located near the Clear Lake Oil Field where some producing wells have short surface casing.
** 1,000 gpm
*** 1,650 gpm

Figure 2



Plug or Monitor Well Recommended

Δp Calculation No Hazard

Initial Review No Hazard
Plug or Monitor Well Recommended Later

1 - WDW 86 1000 gpm
2 - British - American UT B - 1 Plugged by Monsanto & Amoco
3 - WDW 89, 90 1650 gpm
4 - WDW 51 No Hazard; WDW 59, 71 99 - plug or monitor
5 - WDW 130 monitor

DISPOSAL ZONE MODELS

Establishing uniform regulations for a reasonable radius of investigation of artificial penetrations around injection wells is a complex problem due to the many variables that affect pressure. Models of disposal zones have been developed in an attempt to quantify the effects of some of these variables. The relative significance of the values assumed for these variables with respect to reservoir pressure can be assessed in this manner.

ASSUMPTIONS

A primary concern in the preliminary evaluation of a subsurface injection program is to insure that sufficient area around the disposal well is investigated; therefore, parameters required for the determination of the radius at investigation were selected which would result in a conservative analysis. The reservoir, fluid, and injection characteristics assumed for a general analysis are as follows:

1.	porosity	.10 to .30 (percent)
2.	permeability/viscosity ratios	10 to 400 milidarcies/ centipoise (md/cp)
3.	thickness	100 feet
4.	depth of injection zone	5,000 to 7,000 feet
5.	rock compressibility	4.8×10^{-6} to 3.2×10^{-6} psi^{-1}
6.	water compressibility	3.0×10^{-6} psi^{-1}
7.	fluid density (unplugged well bore)	9.0 lb/gal
8.	initial reservoir pressure gradient	.45 psi/ft.
9.	fracture gradient	.65 psi/ft.
10.	maximum injection rates	$\leq$350 gpm (gallons per minute)
11.	project life	25 years

CALCULATION

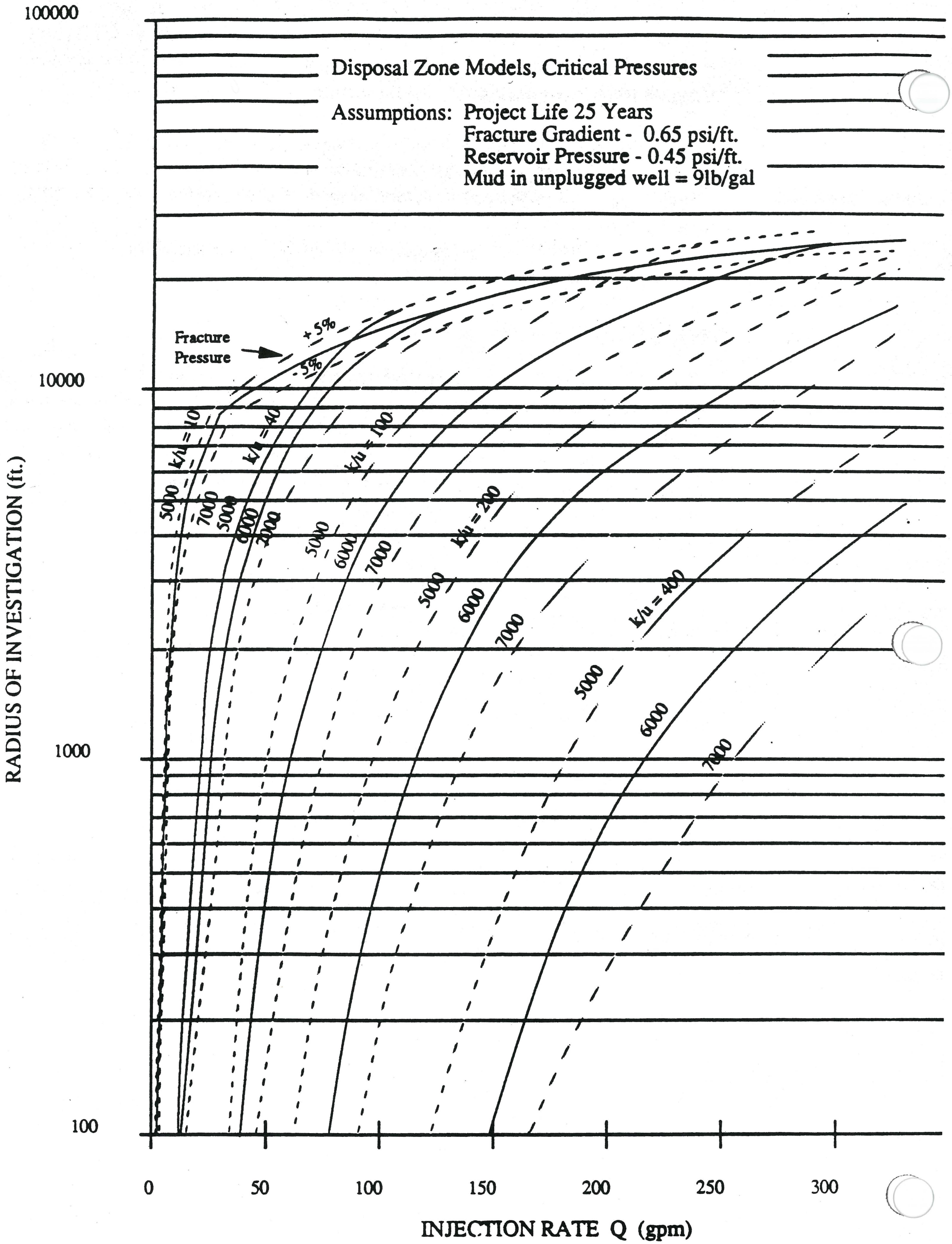
The increase in reservoir pressure resulting from 25 years of injection operations is estimated from the Theis non-equilibrium formula. The critical pressure shown on Figure 3 is the pressure required to displace 9 lb/gal mud in an unplugged well bore. These values are determined at various distances for three assumed depths (5,000, 6,000, and 7,000 feet) and five assumed permeability/viscosity ratios (10, 40, 100, 200, and 400 md/cp). Bottom hole pressure in the injection well is calculated assuming a fluid density of 30-40,000 ppm TDS (specific gravity of 1.04) and the bottom hole pressure in the unplugged well bore is calculated assuming a 9 lb/gal mud is left in the well (specific gravity of 1.085). The data is also plotted for porosity ranging from .10 to .30 and rock compressibility ranging from 4.8 x 10^{-6} psi/lb. A net sand thickness of 100 feet was assumed and various injection rates up to 350 gpm were used.

The maximum injection rate was determined that would not result in reservoir pressure exceeding the fracture pressure and is indicated on Figure 3. The fracture gradient was assumed to be .65 psi/ft and Figure 4 is a graph of the effect of $\pm 5\%$ error in the fracture gradient. Figure 5 is a graph of the effect of an error of $\pm 2\%$ in the initial reservoir pressure estimation.

LIMITATIONS

The limitations of a conservative nature of the disposal zone models presented include: no allowance for friction loss or skin effects, assuming constant injection rates and pressure for 25 years, constant (100 ft) thickness, assuming well bore of improperly plugged well remains open, and assuming hydrologic communication with improperly plugged well. Other limitations include the assumptions of: homogeneous isotropic media, compatibility.

Figure 3



Disposal Zone Models, Critical Pressures
Assumptions: Project Life 25 Years
Fracture Gradient - 0.65 psi/ft.
Reservoir Pressure - 0.45 psi/ft.
Mud in unplugged well = 9lb/gal
Fracture Pressure
+5%
-5%
k/u = 10
k/u = 40
k/u = 100
k/u = 200
k/u = 400
5000
6000
7000
100000
10000
1000
100
RADIUS OF INVESTIGATION (ft.)
0
50
100
150
200
250
300
INJECTION RATE Q (gpm)

Figure 4

Sensitivity of Calculated Radius of Investigation
to Change of Fracture Gradient of ± 5%

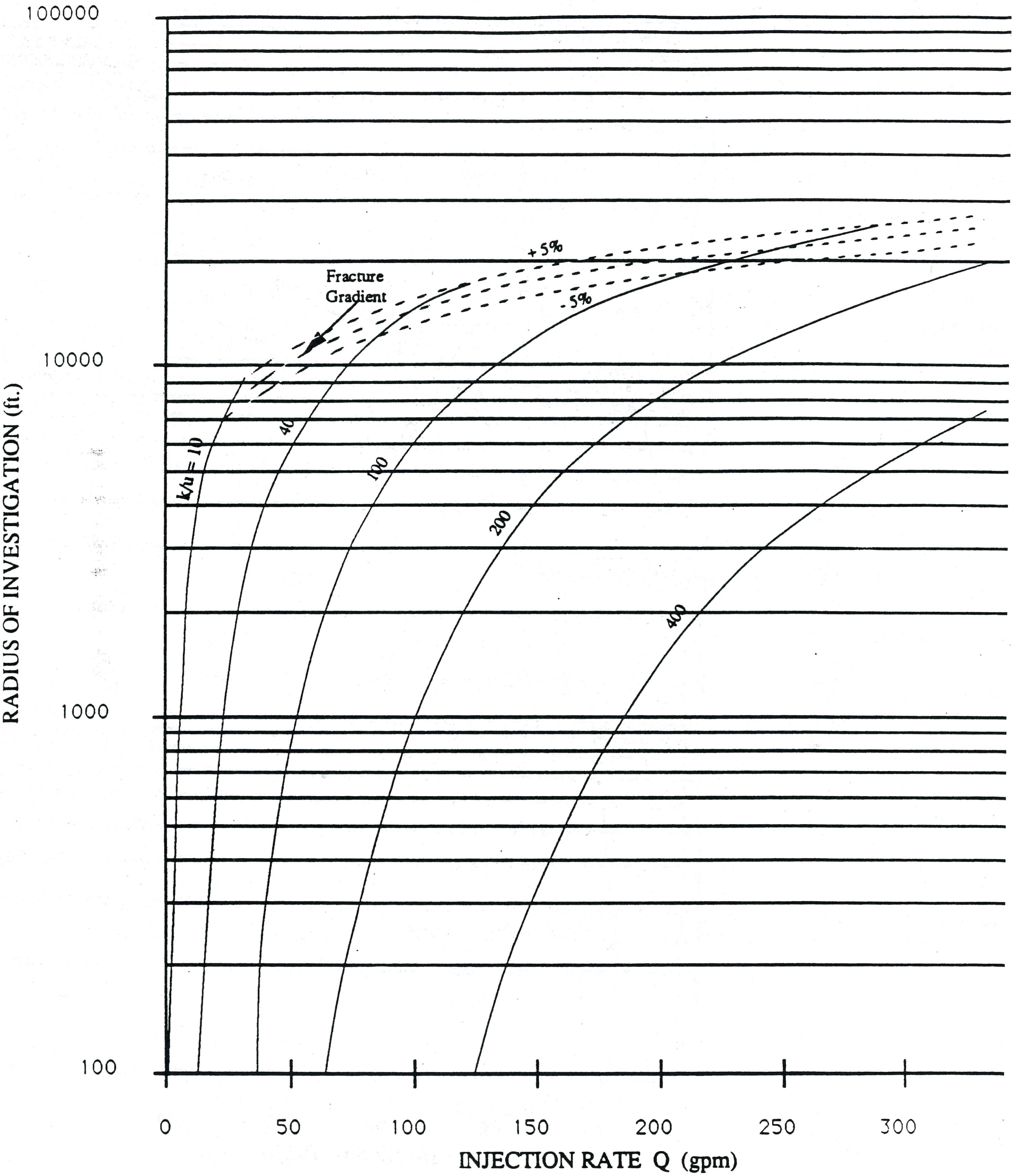
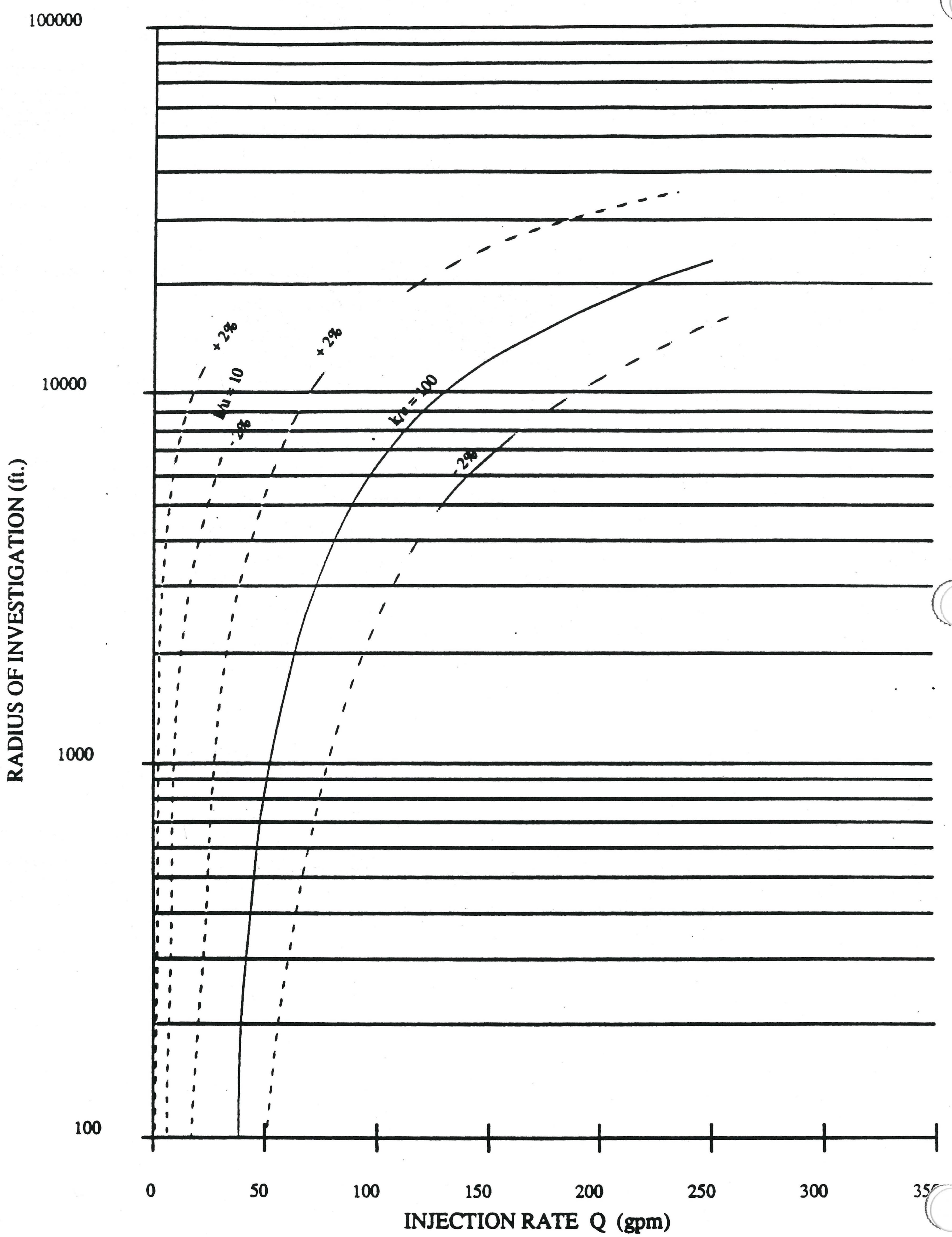


Figure 5

Sensitivity of Calculated Radius of Investigation
to Change of Fracture Gradient of ± 5%



CONCLUSIONS

The review of TDWR Staff Technical Reports prepared during the evaluation of waste disposal well applications indicated that the recommendations as to potential hazards of artificial penetrations were not strictly distance-related. Generally, more recommendations to plug abandoned wells were made for the closer wells evaluated, however, the exceptions show the significance of the assumed values for reservoir, fluid, and injection factors.

The disposal zones models demonstrated the relative significance of the reservoir, fluid and injection variables with respect to areal influence of well injection. The principal factors affecting reservoir pressure increase resulting from well injection appear to be: injection rate, thickness, initial reservoir pressure, permeability/viscosity ratios, method of plugging or completion of investigated wells, and depth of disposal zone. These models emphasize the necessity of obtaining accurate reservoir data for evaluation of pressure increases.

This report only scratches the surface of the possible applications of disposal zone models to predict pressure increases due to well injection. This approach should be very useful in evaluating salt water disposal projects associated with oil and gas production. The data developed from the disposal zone models indicates that the current practice of investigating artificial penetration within a 2½-mile radius around proposed industrial waste disposal wells should be continued, unless justification based on reliable reservoir data indicated otherwise. The modification of the disposal zone models to fit specific injection well sites should be considered, where applicable. Reevaluation of the radius of significant pressure increase should be examined when the reservoir data becomes available after well completion.

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APPENDIX

CALCULATIONS

Fracture Pressures ±5%

Frac. press. = formation breakdown pr.
p = Frac press - bottom hole pressure

	-5%			+5%		
Depth (feet)	Frac. Press.	p	Frac. Press.	p	Frac. Press.	p
5000	3090	840	3250	1000	3410	116
6000	3705	1005	3900	1200	4100	140
7000	4325	1175	4550	1400	4780	160

Formation Fluid Density ±2%

Depth	-2%		Depth	+2%	
5000	2205	145	2350	100	2295
6000			2800	120	
7000			3290	140	

ASSUMPTIONS

d = 100 ft.
t = 9125 days
Q = 350 gpm
Ø = 0.1 to 0.3
a = 4.8×10^{-6} to 3.2×10^{-6} psi^{-1}
B = 3×10^{-6} psi^{-1}
k/u = 10, 40, 100, 200, 400 md/cp
ρ = 1.04 (Formation Fluid)

depth = 5000, 6000, 7000 feet
frac. gradient = 0.65 psi/ft.
frac. pressure = 3250, 3900, 4550 psi
mud density = 9 lb/gal
specific gravity (mud) = 1.085
bottom hole pressure (unplugged well) 2350, 2820, 3290 psi
specific gravity (water) = 1.04
bottom hole pressure = 2250, 2700, 3000 (injector)

$$\Delta h = \frac{1146.Q}{T} W(u)$$

$$U = \frac{1.87 r^2 S}{Tt}$$

Where:

Δh = change in head (feet)
Q = discharge (gpm)
T = Transmissivity (gpd/ft)
W(u) = well function of
r = radius from injection well (feet)
t = time since injection began (days)
S = storage coefficent

$$S = F(w)\, Ø\, m \left(B + \frac{a}{Ø}\right)$$

Where:

F(w) = formation factor
Ø = porosity (percent)
m = thickness of aquifer (inches)
B = compressibility of water psi/lb
a = compressibility of aquifer skeleton psi/lb

APPENDIX

Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp + BHP psi
	9125	50	.10	$4.8x10^{-6}$	$3x10^{-6}$	.00023	10	1.04	5000	10	1716	3966
		30								10	1030	3280
										8000	105	2355
		50							6000	10	1716	4540
		35								10	1201	3900
										8000	123	2353
		50							7000	10	1716	4870
		40								10	1375	4525
										8000	141	3290
	9125	50	.10	$4.8x10^{-6}$	$3x10^{-6}$	.00023	40	1.04	5000	10	470	2820
										5500	103	2250
									6000	10	470	3170
										4000	121	2821
									7000	10	470	3620
										3000	137	3287
		100							5000	10	940	3190
										14000	102	2350
									6000	10	940	3640
										12000	118	3288
									7000	10	940	4090
										10000	138	3290
		105							5000	10	985	3235
										15000	100	2350
		130							6000	10	1200	3920
										15000	123	2920
		150							7000	10	1408	4560
										15000	142	3292
		50	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	100	1.04	5000	10	198	2450
										750	98	2350
									6000	10	198	2900
										300	120	2820
									7000	10	198	3350
										100	140	3290

Parameter	Time	Q	Ø	a	B	S	k/u	ρ	Depth	Radius	Δp	Δp + BHP
Units	Days	gpm	%	psi/lb	psi/lb		md/cp	ratio	ft.	ft.	psi	psi
	9125	100	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	100	1.04	5000	10	397	2650
										6000	99	2350
									6000	10	397	3100
										4000	120	2820
									7000	10	397	3550
										2500	140	3290
		200							5000	10	793	3050
										18000	100	2350
									6000	10	793	3500
										14000	121	2820
									7000	10	793	3950
										11000	140	3290
		252							5000	10	1000	3250
										23000	100	2350
		300							6000	10	1200	3900
										22500	120	2820
									7000	10	1400	4550
										22500	140	3290
	9125	200	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	200	1.04	5000	10	410	2660
										8000	100	2350
									6000	10	410	3100
										5500	120	2820
									7000	10	410	3560
										3500	140	4550
		300							5000	10	619	2870
										17000	100	2350
									6000	10	619	3320
										13000	120	2820
									7000	10	619	3770
										10000	140	3290
	9125	300	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	400	1.04	5000	10	321	2570
										5500	100	2350
									6000	10	321	3020
										3200	120	2820

Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp + BHP psi
									7000	10	321	3470
										1800	140	3290
		30								10	1040	2390
										9000	104	2350
		35							6000	10	1219	3919
										9000	122	2820
									7000	10	1393	4543
										9000	140	3290
		50	.30	$3.2X10^{-6}$	$3x10^{-6}$	.000185	100	1.04	5000	10	200	2450
										750	100	2350
									7000	10	200	3350
										130	141	3290
		250							5000	10	1005	3250
										25000	100	2350
		350							7000	10	1407	4556
										25000	141	3290
	9125	263	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	100	1.04	5000	10	1045	
										16000	145	
		200								10700	145	
		100								2200	145	
		50								100	145	
		241								10	955	
		1100								35000	55	
		200								31000	55	
		100								16000	55	
		50								4800	55	
		25								450	55	
	9125	111.5	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	40	1.04	5000	10	104[illegible]	
										10800	145	
		100								9400	145	
		50								2600	145	
		35								1400	145	
		25								225	145	
		102								10	955	
										23000	55	

Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp+BHP psi
		60								15000	55	
		30								6600	55	
	9125	50	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	10	1.04	5000	10	1716	
		30.5								10	1046	
										6000	144	
		20								3400	145	
		10								700	145	
		27.8								10	955	
										12000	55	
										9800	55	
		10								5000	55	

APPENDIX 4-8

Appendix 4-8

Determining the Area of Review for Industrial Waste Disposal Wells (Barker, 1981)

DETERMINING THE AREA OF REVIEW FOR

INDUSTRIAL WASTE DISPOSAL WELLS

APPROVED BY SUPERVISORY COMMITTEE:

DETERMINING THE AREA OF REVIEW FOR INDUSTRIAL WASTE DISPOSAL WELLS

BY

STEPHEN EUGENE BARKER, B. S.

REPORT

Presented to the Faculty of the Graduate School

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN ENGINEERING

THE UNIVERSITY OF TEXAS AT AUSTIN

December 1981

Acknowledgment

I would like to thank the United States Navy for this opportunity to broaden the foundation of knowledge required to support my career as a naval officer. I would like to acknowledge the efforts of Drs. R. E. Collins and A. L. Podio in their review and critique of this report. I also desire to thank Mr. Bob Kent, Underground Resource Management, Inc. for his assistance and support in providing the necessary literature and data required to make this report possible.

S. Barker

University of Texas

Austin, Texas

October, 1981

Abstract

The area of review is defined by the radial distance from waste disposal wells in which the injection formation fluid pressure increases sufficiently to force formation fluids and/or injected wastes up abandoned well bores to contaminate underground sources of drinking water. The cost of corrective action required to prevent such contamination within the area of review can be considerable. To minimize the costs associated with subsurface disposal operations an appropriate area of reveiw must be adequately defined. This report provides a simplified procedure which can be utilized to determine a minimum area of review which can be safely applied to a given subsurface injection operation.

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INTRODUCTION

Introduction

The increased fluid pressure in a disposal zone which results from a waste injection operation may force injected and/or formation fluid to migrate up an abandoned well bore which penetrates the injection formation. Should migration occur, commingling with underground sources of drinking water may result. When a waste injection well reaches its design life (typically twenty years) the radial distance form the injector at which the potential for fresh water contamination exists is defined as the area of review. Environmental regulations require the well operator to take corrective action, as required, at each abandoned well within the area of review to insure that contamination does not occur. The cost of corrective action can be significant. Therefore, it is essential that the area of review be adequately defined before corrective measures are undertaken. This paper presents a simplified procedure which can be utilized to calculate the area of review.

If an abandoned well was not produced, drilling mud remains in the well bore since it has no means of escape. To evaluate the potential for fluid migration up such a well bore the forces which act on this static mud column within the well bore must be determined. In most cases the wells were drilled with water base drilling muds which develop a gel structure when allowed to remain quiescent. To initiate flow up the abandoned well bore the fluid pressure in the formation must exceed the sum of the static mud column pressure (Ps) and the gel strength pressure (Pg). The area of review is defined as that area within which the well life formation pressure (P_f) is greater than (P_s) + (P_g).

Theoretical Development

Figure (1) represents a vertical force diagram of the static mud column in an abandoned well bore. The equation for the force balance takes the following form,

$$w + 2\pi \, r_w hGS = P_f \; \pi r_w^2 - P_t \, \pi r_w^2 \quad (1\text{-}1)$$

simplify and let $r_w = \frac{D}{2}$, equation 1-1 becomes

$$P_f - P_t = 0.052\rho h + \frac{4hGS}{D} \quad (1\text{-}2)$$

neglecting surface pressure (P_t) and converting to consistent field units,

$$P_f = 0.052 \cdot \rho_{min} \, h + 3.33 \times 10^{-3} \; \frac{Gsh}{D_{max}} \quad (1\text{-}3)$$

Where: $P_s = 0.052 \, \rho_{min} h$ -- represents the static mud column pressure

$P_g = 3.33 \times 10^{-3} \; \frac{Gsh}{D_{max}}$ -- represents the gel strength pressure

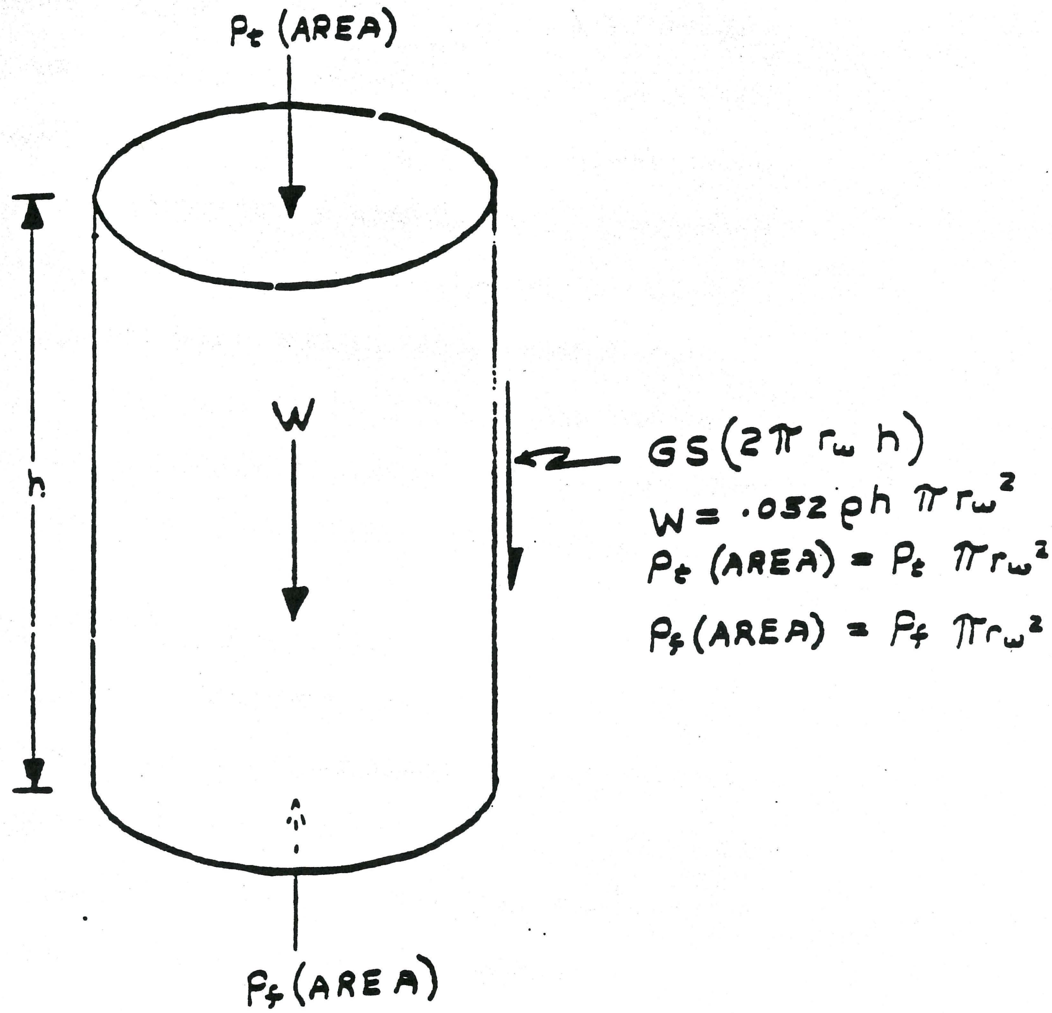


FIGURE 1
STATIC MUD COLUMN
FORCE BALANCE DIAGRAM

P_f represents the well life formation pressure. The pressure which results at a radial distance r from the injection well at time t after the start of injection of a waste of small and constant compressibility at a constant rate Q throughout the life of the well into an infinite, isotropic, homogeneous, horizontal reservoir of uniform thickness and porosity is well approximated by,

$$P_f = Pi - \frac{QuB}{4\pi kh} E_i \left(\frac{-\phi ucr^2}{4kt} \right) \quad (1\text{-}4)$$

<u>Procedure for Determining Tha Area of Review</u>

The proposed procedure for determining the area of review for waste injection wells is predicated on the following basic assumptions:

1.) The static mud column extends to the surface and is uniform in density.

2.) Abandoned well bore diameters used in calculations are equal to the bit diameter plus two inches where bit refers to that used to drill the hole at the depth of the injection formation.

3.) The gel strength applied to all wells is 20 $lbs/100\ ft.^2$

4.) Injection pressures will not exceed the fracture pressure of the injection formation.

5.) Known abandoned wells for which no data are available will be assigned the minimun mud density and the largest bit diameter noted for all wells within a 2½ mile radius of the injector.

6.) None of the abandoned wells were completed and produced.

7.) All pressures are calculated at the top of the injection formation.

8.) All abandoned wells were drilled with water base muds.

9.) None of the abandoned wells are plugged.

Utilizing the developed theory and applying the basic assumptions, it is possible to compare P_f with $P_s + P_g$. The area of review will be defined by the radial distance from the injection well at which $P_f > P_s + P_g$.

The procedure employs an iterative process to determine the appropriate area of review for a given injection operation. The first iteration considers all abandoned wells within a 2½ mile radius of the injection wells. Once an area of review is determined, the process is repeated considering only those wells within the determined area of review. The iterative process is repeated until both the minimum mud density (ρ_{min}) and maximum bit diameter at the depth of the injection formation (Dmax) for the abandoned wells within the previously defined area of review no longer vary with the iterations. When ρ_{min} and Dmax stabilize the resulting area of review is the true area of review for the specified injection operation. The procedure is demonstrated by the following example.

Example

An industrial waste injection operation is proposed to dispose of 500 gal/min of waste for a period of 20 years. The waste will be injected into a sand formation at a depth of 5000 ft. employing two injection wells each operating at a rate of 250 gal/min. Figure (2) displays the abandoned well locations with respect to the injection wells. The mud densities and bit diameters for all abandoned wells are as noted in Table 1. The pertinent formation and fluid characteristics for the proposed operation are presented in Figure (3).

By means of a digital computer it is possible to use the developed theory to plot P_f, P_s, and $P_s + P_g$ as a function of the radial distance from the injection well as shown in Figure (3). The area of review is indicated by the radial distance from the injector at which the well life formation pressure intersects the constant pressure line $P_s + P_g$. For injection operations which utilize multiple injectors at a single site, the total flow of the wells can be input as one well and the area of review adequately approximated as that of a single well. Likewise, for wells of variable flow rate, an average, constant flo[w] rate can be utilized to obtain satisfactory approximate results. P_g is calculated by using the largest bit diameter noted on well logs for all abandoned wells withi[n] a radial distance of 2½ miles of the injectors.

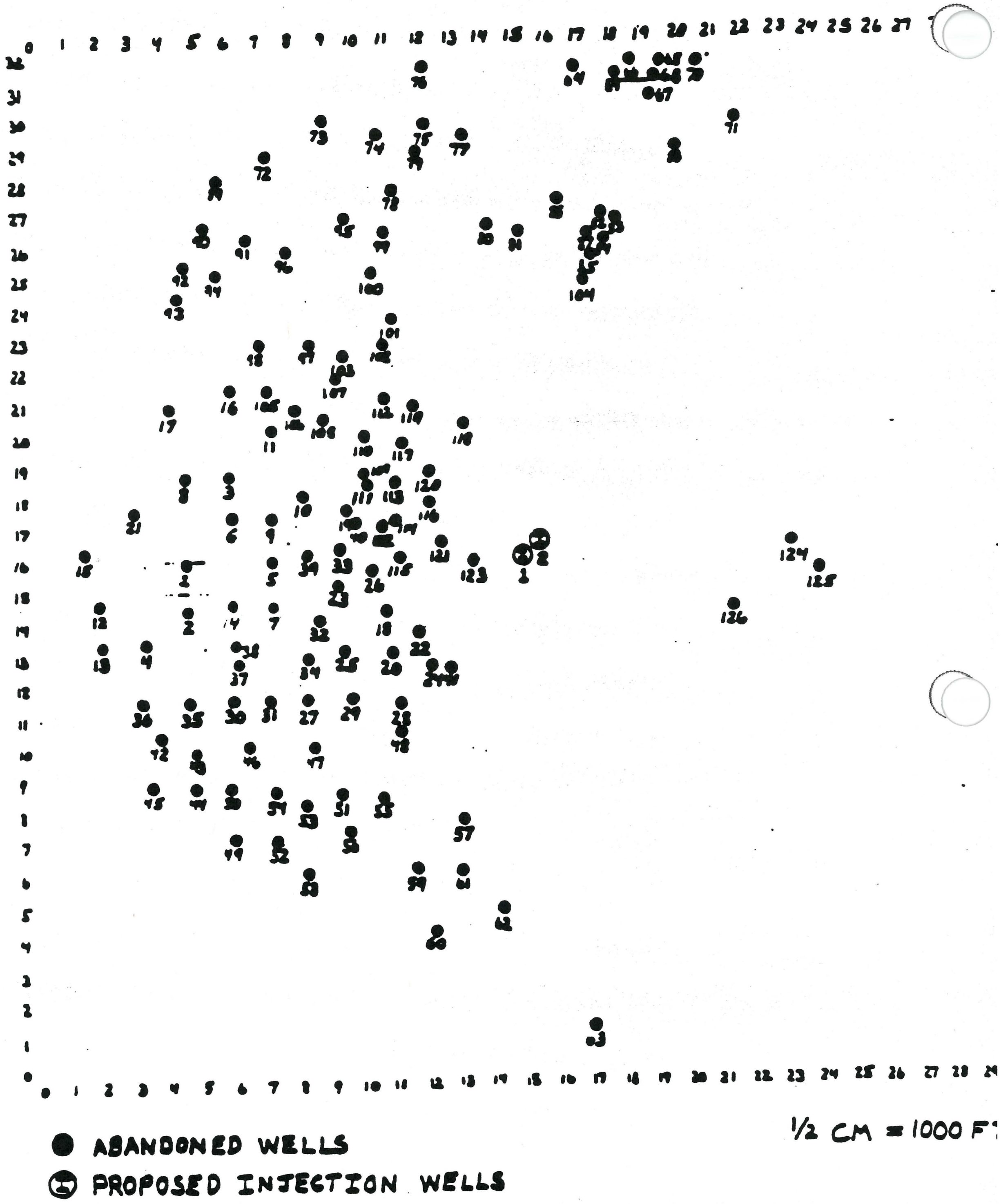
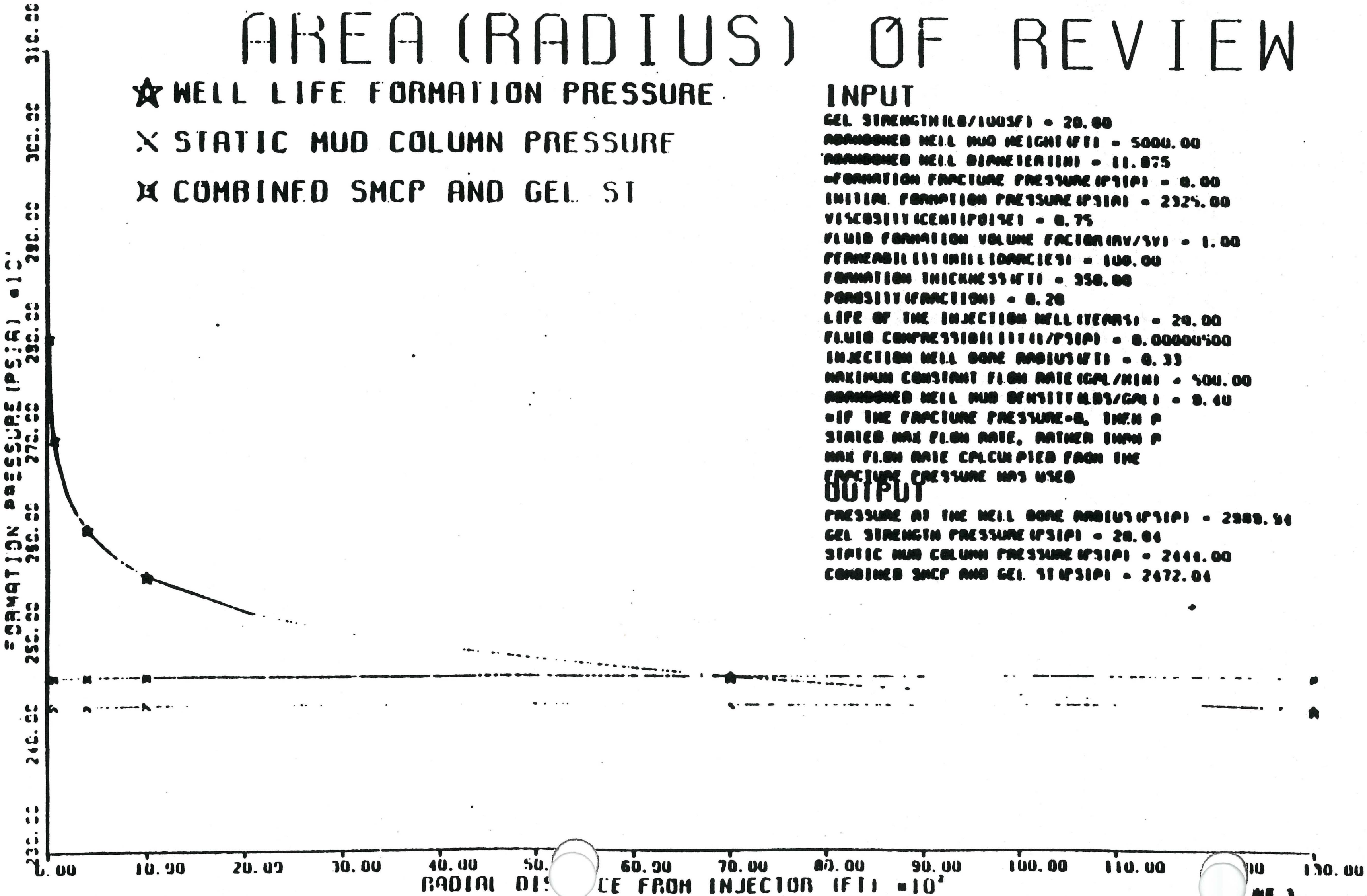


FIGURE 2. Abandoned and injection well locations

TABLE 1

INFORMATION PERTINENT TO EACH ABANDONED WELL

WELL #	X-CORD	Y-CORD	DENSITY lb/gal	BIT DIA in
1	4650	19900	9.4	7.875
2	4700	14550	10.5	7.875
3	5925	18600	10.5	7.875
4	3375	13275	10.5	71875
5	7350	15900	10.7	7.875
6	6025	17350	11.8	7.875
7	7375	14500	10.7	8.75
8	4575	18600	10.7	7.875
9	7350	17350	10.7	7.875
10	8300	17950	10.6	7.875
11	7325	20075	10.6	7.875
12	1950	14600	10.6	7.875
13	2000	13250	10.4	8.75
14	6050	14550	10.8	7.875
15	1525	16375	10.7	7.875
16	6050	21275	10.6	7.875
17	4175	20850	10.1	6.5
18	10800	14300	12.9	6.75
19	9600	17550	10.6	7.875
20	10950	12950	12.5	7.875
21	3050	17475	10.5	7.875
22	11825	13650	12.4	7.875
23	9350	15100	10.7	7.875
24	12150	12600	12.7	7.875
25	9525	13075	11.5	7.875
26	10450	15600	10.1	7.875
27	8400	11575	10.7	7.875
28	11225	11400	10.4	8.75
29	9700	11600	9.5	8.75
30	6000	11500	9.5	7.875
31	7250	11500	9.8	7.875
32	8750	14000	9.6	7.875
33	9800	16275	9.7	7.875
34	8400	12800	9.5	7.875
35	4675	11475	10.0	7.875
36	3300	11500	9.7	7.875
37	6150	12725	9.7	9.75
38	6100	13225	9.8	7.875
39	8400	16100	9.4	7.875
40	9825	17100	9.5	7.875
41	12700	12450	13.4	7.875
42	3800	10350	10.1	7.875
43	4850	9875	10.5	7.875
44	4850	8800	10.5	7.875
45	3550	8775	10.6	7.875
46	6450	10075	9.8	7.875
47	8525	10050	10.3	7.875
48	11200	10500	12.5	7.875
49	5950	7200	10.1	7.875
50	5800	8800	9.4	7.875
51	9300	8450	11.0	8.75
52	7325	7075	11.0	8.75
53	8250	8150	10.1	8.75
54	7150	8650	9.5	8.75
55	10650	8375	9.7	7.875
56	9550	7450	9.4	7.875
57	13000	7600	10.1	7.875
58	8275	6075	10.2	7.875
59	11650	6175	9.8	7.875
60	12100	4175	10.5	7.875
61	12975	6150	10.3	7.875
62	14250	4875	10.1	7.875
63	16850	1325	10.5	7.875
64	16850	31500	11.0	8.75
65	19500	31650	10.9	7.625
66	18700	31650	10.5	9.875
67	19200	30500	10.5	9.875
68	19400	31100	10.2	9.875
69	18100	31200	10.2	7.875
70	20600	31550	12.1	9.875
71	21750	29700	10.7	8.75
72	7350	28800	17.0	8.50
73	9000	29900	10.7	8.625
74	10750	29400	10.4	9.875
75	12200	29750	10.0	7.875
76	12250	31500	10.1	7.875
77	13400	29400	11.0	8.75
78	11250	27650	10.0	7.875
79	11900	28850	10.4	7.875
80	14100	26600	10.4	7.875
81	15100	26400	9.9	9.875
82	17650	26850	10.6	8.75
83	18025	26700	10.3	9.875
84	17700	26075	10.3	9.875
85	17225	25475	10.3	8.75
86	16300	27275	10.5	7.625
87	17200	26200	10.1	7.875
88	19925	28975	10.3	9.625
89	5700	28075	11.2	7.875
90	5325	26600	10.1	7.875
91	6650	26200	10.2	8.75
92	4725	25325	9.9	7.875
93	4425	24375	10.2	8.75
94	5600	25000	10.8	8.625
95	9625	24825	10.5	7.875
96	7775	25800	10.5	8.75
97	8650	22775	10.4	7.875
98	6975	22800	10.5	7.875
99	10875	26400	10.2	7.875
100	10450	25025	10.3	7.875
101	11875	23575	10.8	7.875
102	10775	22700	10.5	7.875
103	9550	22375	10.5	7.875
104	17000	24750	10.7	9.875
105	7175	21350	10.6	7.875
106	8000	20675	10.7	7.875
107	9200	21675	10.8	7.875
108	8875	20425	10.6	7.875
109	10100	18650	10.9	7.875
110	10175	19850	11.1	7.875
111	10150	18400	11.0	7.875
112	10825	21000	10.5	7.875
113	11100	18350	10.5	7.875
114	11200	17150	11.6	7.875
115	11325	15975	11.5	7.875
116	12225	17750	11.0	7.875
117	11425	19600	11.1	7.875
118	13325	20125	11.2	7.875
119	11700	20750	9.7	7.875
120	12250	18700	9.7	7.875
121	12450	16500	9.5	7.875
122	10700	17000	9.7	7.875
123	13475	15800	11.6	7.875
124	23300	16250	10.5	7.875
125	24050	15475	10.6	8.75
126	21550	14325	10.2	7.875


AREA (RADIUS) OF REVIEW
WELL LIFE FORMATION PRESSURE
STATIC MUD COLUMN PRESSURE
COMBINED SMCP AND GEL ST
INPUT
GEL STRENGTH (LB/100SF) = 20.00
ABANDONED WELL MUD HEIGHT (FT) = 5000.00
ABANDONED WELL DIAMETER (IN) = 11.875
*FORMATION FRACTURE PRESSURE (PSIA) = 0.00
INITIAL FORMATION PRESSURE (PSIA) = 2325.00
VISCOSITY (CENTIPOISE) = 0.75
FLUID FORMATION VOLUME FACTOR (RV/SV) = 1.00
PERMEABILITY (MILLIDARCIES) = 100.00
FORMATION THICKNESS (FT) = 350.00
POROSITY (FRACTION) = 0.20
LIFE OF THE INJECTION WELL (YEARS) = 20.00
FLUID COMPRESSIBILITY (1/PSIA) = 0.00000500
INJECTION WELL BORE RADIUS (FT) = 0.33
MAXIMUM CONSTANT FLOW RATE (GAL/MIN) = 500.00
ABANDONED WELL MUD DENSITY (LBS/GAL) = 9.40
*IF THE FRACTURE PRESSURE=0, THEN A
STATED MAX FLOW RATE, RATHER THAN A
MAX FLOW RATE CALCULATED FROM THE
FRACTURE PRESSURE WAS USED
OUTPUT
PRESSURE AT THE WELL BORE RADIUS (PSIA) = 2389.94
GEL STRENGTH PRESSURE (PSIA) = 28.04
STATIC MUD COLUMN PRESSURE (PSIA) = 2444.00
COMBINED SMCP AND GEL ST (PSIA) = 2472.04
FORMATION PRESSURE (PSIA) *10¹
310.00
300.00
290.00
280.00
270.00
260.00
250.00
240.00
230.00
0.00
10.00
20.00
30.00
40.00
60.00
70.00
80.00
90.00
100.00
110.00
130.00
RADIAL DIS CE FROM INJECTOR (FT) *10²

This provides a worst case design. Similarly, P_s is calculated utilizing the minimum mud density obtained from logs for the same radial distance from the injector. Figure (3) indicates the area of review for the example using these criteria as approximately 7000 ft.

Figure (4) is a computer generated plot which displays the location of the isobar on which $P_f = P_s + P_g$ and indicates those abandoned wells which lie within the area of review defined by the isobar.

Considering only the abandoned wells contained within the isobar defined in Figure (4), the area of review is recalculated. The new area of review, as noted in Figures (5) and (6), is an area encompassed by a radial distance of approximately 3800 ft from the injection wells which contains only 3 abandoned wells. It is noted that in the second iteration the minimum mud density (ρ_{min}) has increased from 9.4 to 9.5 lbs/gal and the maximum corrected bit diameter (D_{max}) has decreased from 11.875 in to 9.875 in. Another iteration of the procedure yields the same values for ρmin and D_{max}. Therefore, the area of review defined is the true area of review for the specified injection operation.

Corrective action must be considered for all wells within the area of review. Therefore, each of the three wells should be analyzed on an individual basis using the

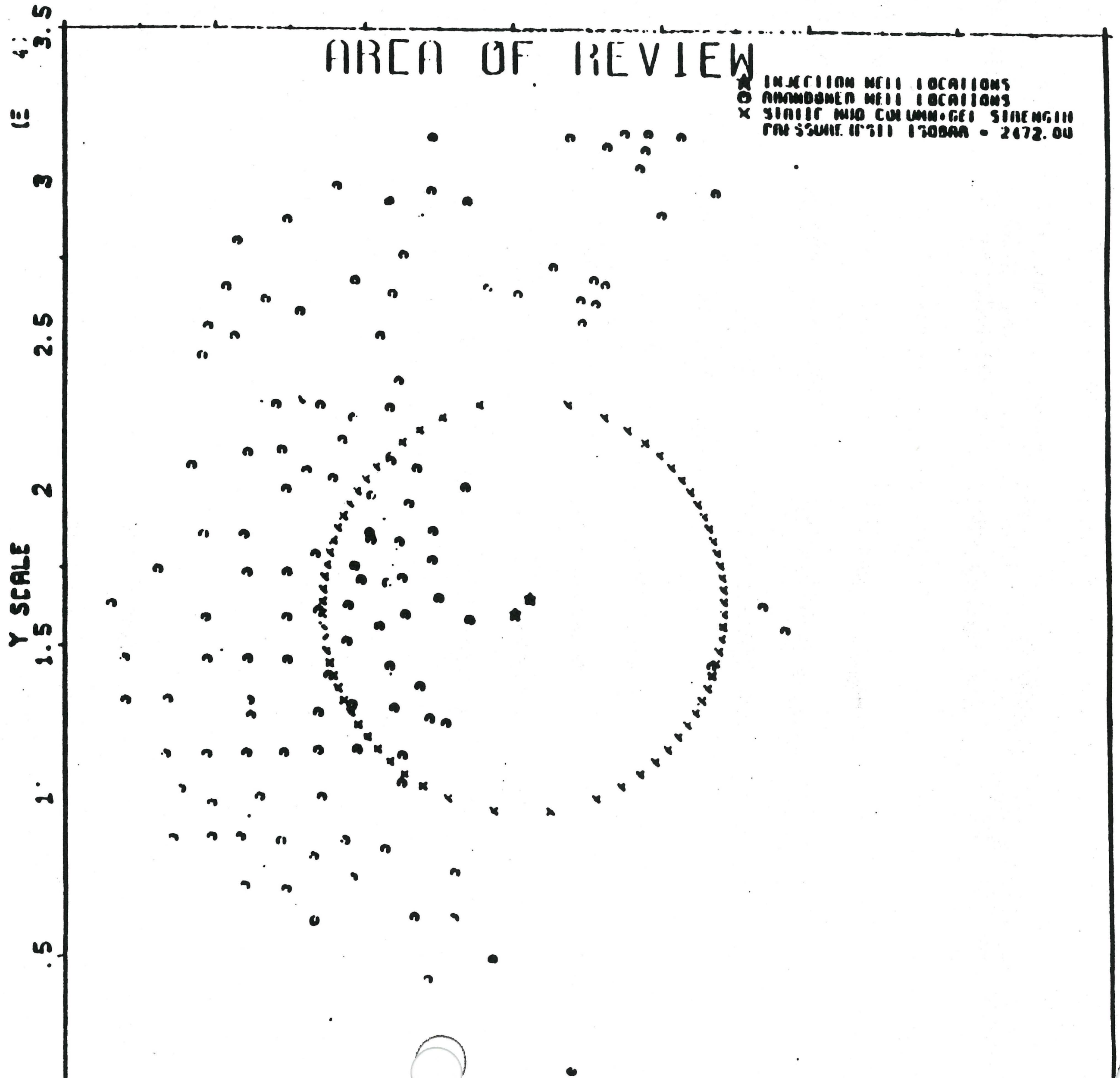
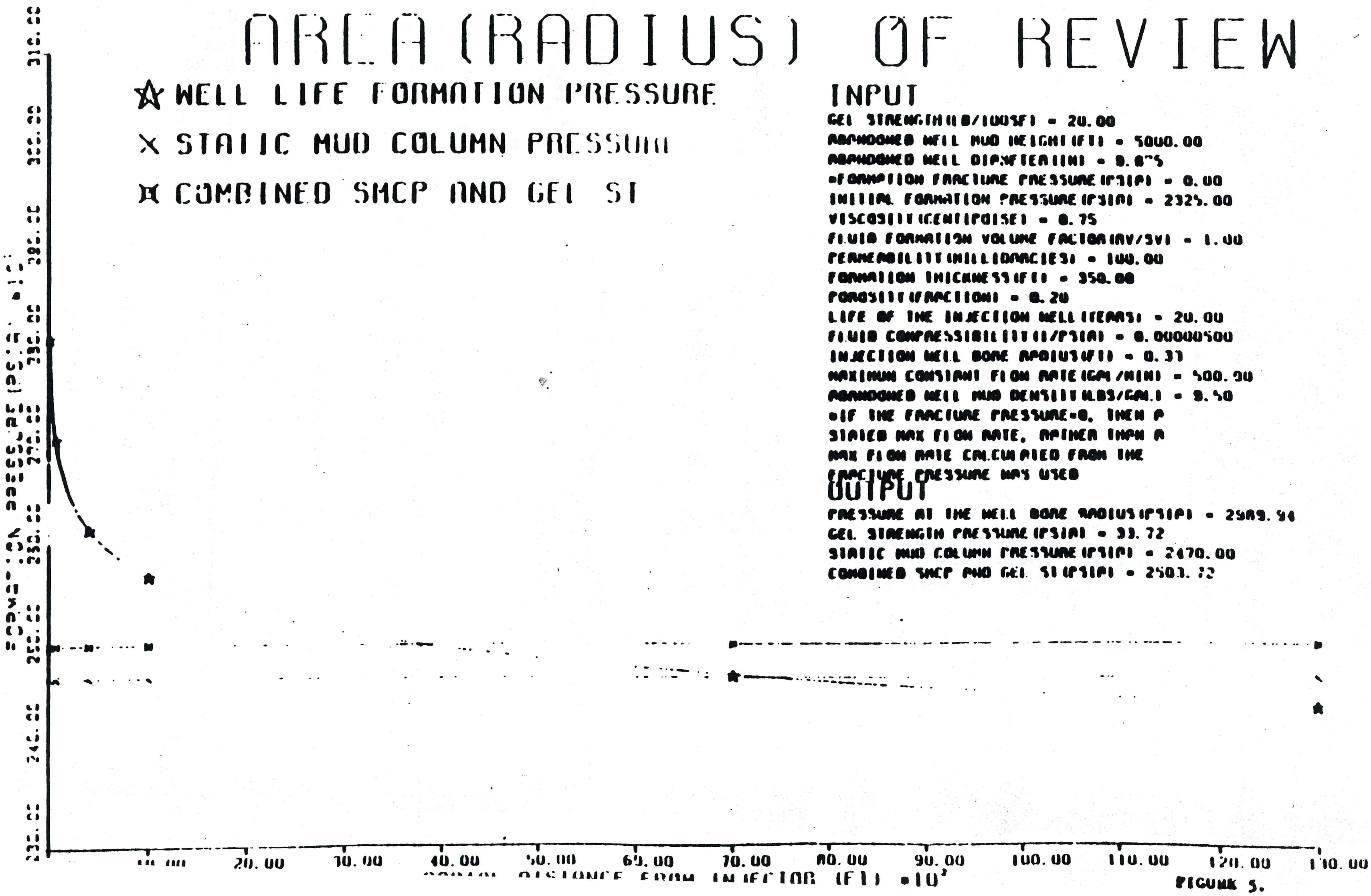
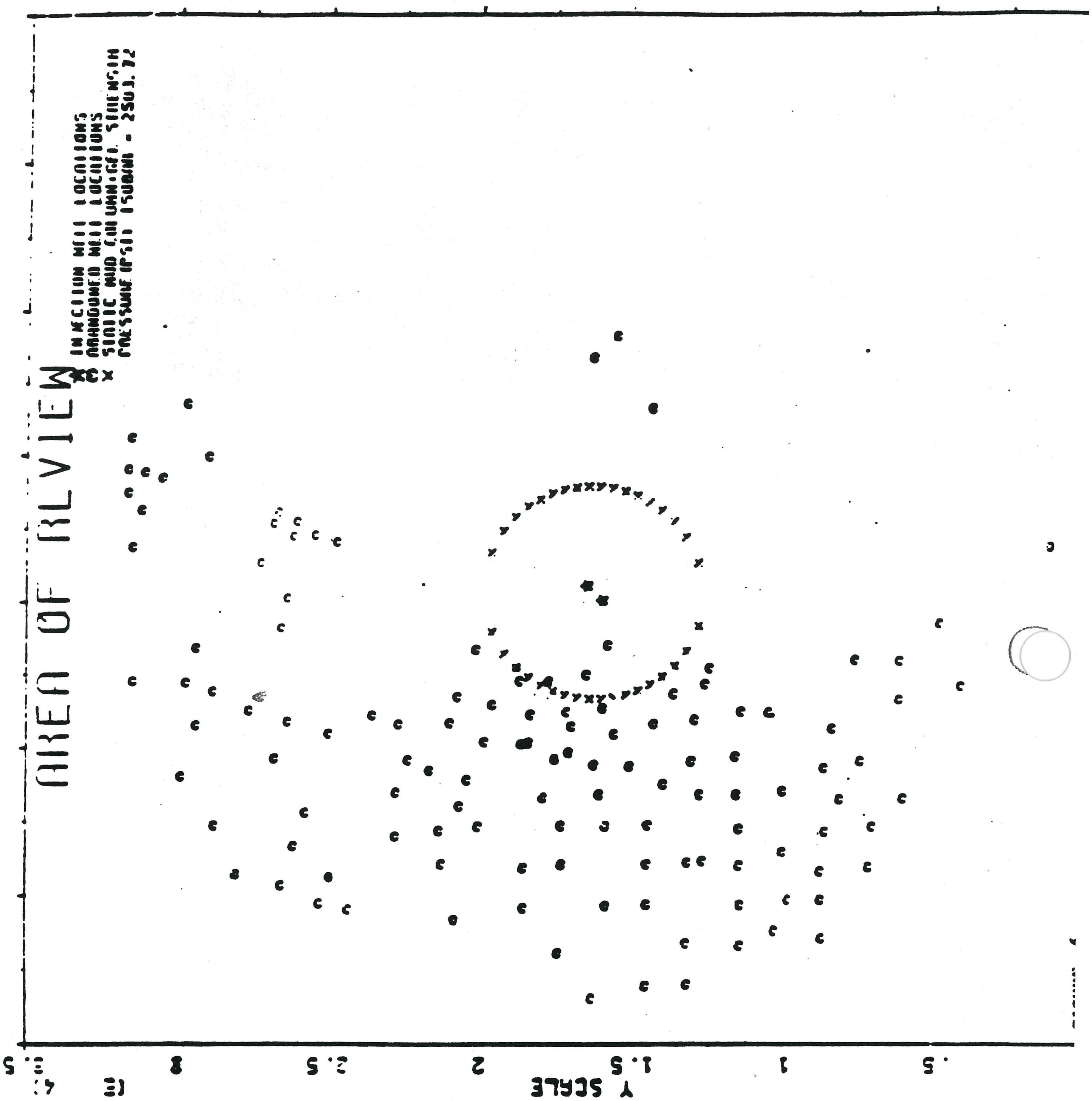

AREA OF REVIEW
INJECTION WELL LOCATIONS
ABANDONED WELL LOCATIONS
STATIC MUD COLUMN-GEL STRENGTH
PRESSURE (PSI) ISOBAR = 2472.00
Y SCALE
3.5
3
2.5
2
1.5
1.
.5

FIGURE 4



AREA (RADIUS) OF REVIEW
WELL LIFE FORMATION PRESSURE
STATIC MUD COLUMN PRESSURE
COMBINED SMCP AND GEL ST
INPUT
GEL STRENGTH(LB/100SF) = 20.00
ABANDONED WELL MUD HEIGHT(FT) = 5000.00
ABANDONED WELL DIAMETER(IN) = 8.875
*FORMATION FRACTURE PRESSURE(PSIA) = 0.00
INITIAL FORMATION PRESSURE(PSIA) = 2325.00
VISCOSITY(CENTIPOISE) = 0.75
FLUID FORMATION VOLUME FACTOR(RV/SV) = 1.00
PERMEABILITY(MILLIDARCIES) = 100.00
FORMATION THICKNESS(FT) = 350.00
POROSITY(FRACTION) = 0.20
LIFE OF THE INJECTION WELL(YEARS) = 20.00
FLUID COMPRESSIBILITY(1/PSIA) = 0.00000500
INJECTION WELL BORE RADIUS(FT) = 0.33
MAXIMUM CONSTANT FLOW RATE(GAL/MIN) = 500.00
ABANDONED WELL MUD DENSITY(LBS/GAL) = 9.50
*IF THE FRACTURE PRESSURE=0, THEN A
STATED MAX FLOW RATE, RATHER THAN A
MAX FLOW RATE CALCULATED FROM THE
FRACTURE PRESSURE WAS USED
OUTPUT
PRESSURE AT THE WELL BORE RADIUS(PSIA) = 2589.94
GEL STRENGTH PRESSURE(PSIA) = 33.72
STATIC MUD COLUMN PRESSURE(PSIA) = 2470.00
COMBINED SMCP AND GEL ST(PSIA) = 2503.72
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
110.00
120.00
130.00
RADIAL DISTANCE FROM INJECTOR (FT) *10²

FIGURE 5.


AREA OF REVIEW
INJECTION WELL LOCATIONS
ABANDONED WELL LOCATIONS
Y SCALE
.5
1
1.5
2
2.5
3

developed theory. After individual analysis it is apparent that well number 121 is capable of allowing fluid to migrate up its well bore. If records indicate that well number 121 was properly plugged no corrective action would be required prior to conducting the proposed waste injection operation.

Conclusions

1. The costs associated with record searches and field surveys undertaken to determine the plugging history of abandoned wells can be avoided if the wells lie outside the area of review determined by the described procedure.
2. The costs associated with plugging abandoned wells located outside the calculated area of review can also be avoided.
3. Since the pressure cone resulting from the injection operation falls off quickly the size of the area of revie is extremely sensitive to small pressure differences at large radial distances from the injector.
43. The number of abandoned wells which fall inside the area of review can be reduced by varying injection well locations, injection rates and the injection formation.

NOMENCLATURE

D - Diameter of the well bore (in)

Dmax - Maximum bit diameter (in)

GS - Gel strength (lbs/100 Ft^2)

h - height of mud column (Ft)

r_w - well bore radius (in)

P_f - formation pressure (Psi)

P_g - gel strength pressure (Psi)

P_s - Static mud column pressure (Psi)

P_t - air pressure (Psi)

W - weight of the mud column (16s)

ρ - mud density (lbs/gal)

ρ_m - minimun mud density (lbs/gal)

CHAPTER II

BACKGROUND

The Environmental Atmosphere

The rapid rate of industrial developement that exists in a highly industrialized country like the United States has given birth to a myriad of environmental problems which resist time and linger to haunt man for decades. For example, the extensive use of polychlorinated biphenols (PCB's) as a cooling medium in electric transformers and capacitors presents a current problem which remains to be solved. The widespread use of PCB's has resulted in the distribution of millions of gallons of nonbiodegradeable, carcinogenic waste in transformers located in our factories, schools, office buildings, and neighborhoods. Many of the transformers are leaking and the public is unknowingly being exposed to the carcinogenic waste. Extensive use of the insecticide DDT and the insulating material asbestos has presented similar environmetnal hazards. An environmental dilemma exists in the case of PCB's and other hazardous wastes. Environmental groups have strongly opposed the establishment of hazardous waste disposal sites within their geographic area of interest. The proposed disposal sites would utilize advanced technology to provide the best means of disposal presently available. Without the establishment of the needed waste disposal facilities t[illegible] wastes will remain interdispersed throughout the populace where they pose a greater risk to man and the environment. It becomes apparent that the government, industry and the general public must cooperate and pool their resources if a logical and acceptable course of disposal action is to be pursued. The total dominance and influence of one interest group over another may destroy the balance required to allow growth and developement to continue while minimizing any adverse impact on the environment.

The well managed and organized efforts of environmentally conscious organizations have increased the public awareness of the dangers which result from the improper disposal of hazardous waste. These efforts and extensive media coverage of the environmental catastrophies resultin form the improper disposal of hazardous wastes (i. e. Love Canal in Niagara Falls, New York) have fueled the proliferation of federal, state and local regulations designed to protect man and the environment. These regulations, which govern all aspects of hazardous waste disposal, necessitate considerable capital investments by industry in their efforts to attain compliance. Although few can dispute the need to regulate hazardous waste disposal, some of the regulations promulgated towards this end can be questioned. Some requirements appear to be predicated on political, social or historical preferences or practices, rather than evolving from sound engineering and scientific principals which provide a means of verification and/or justification. This approach has resulted in the unnecesssary expendature by industry of funds to gain compliance with the regulations.

The Goal of Industrial Waste Disposal Regulations

The primary goal of the hazardous waste regulations which govern the disposal of liquid hazardous waste is to protect underground sources of drinking water. The originators and enforcers of the regulations must not loose sight of this goal. The regulations should be enforced in a manner which allows the waste generator to utilize the most advanced waste disposal technology available if it can be demonstrated that the technology provides the best environmental alternative for disposal. When more than one disposal option can be pursued, the regulatory agencies should encourage the generator to pursue the best environmental option. The regulations should not be so restrictive that they eliminate the waste disposal option which presents the least potential for contamination of ground water sources of drinking water.

Liquid Waste Disposal Options

Biological Treatment, Incineration, Off-site Disposal, On-site Landfill, Surface Impoundment, and Subsurface Injection are liquid waste disposal options available to the waste generator. Surface impoundment (evaporation) is the most common and frequently utilized means of disposal for liquid hazardous waste. Annually, Texas generates and disposes of 13.3 billion gallons of industrial waste in surface impoundments.[1] Since few of the impoundments are lined, the potential for contamination of ground water sources of drinking water is high. Even those evaporation impoundments located on low permeability clays present a contamination risk since no natural material is impermeable. The cost of modifying existing impoundment facilities to eliminate the contamination risk and/or to comply with regulatory requirements is prohibitive. To eliminate the risk other sources of disposal must be pursued. A preliminary study of surface impoundments examined 85 case histories of ground water contamination resulting from surface impoundment.[2] The study emphasizes the risks that result from utilizing surface impoundment disposal methods.

To eliminate the contamination which is inherent with many of the existing surface impoundments it has become necessary to pursue alternate means of hazardous waste disposal. A disposal means which has gained in popularity during the past four decades is the subsurface disposal of wastes by injection into subsurface formations containing salt water. Subsurface injection removes the waste from the biosphere and confines it in deep geologic formations. Since 1961 over 42 billion gallons of waste has been disposed of by subsurface injection in Texas alone.[1]

Summary

As of 1973, 20% of the total United States water needs have been fulfilled utilizing ground water. Ground water fulfills more than 85% of the public water needs in several states (Mississippi, Florida, New Mexico, Idaho and Hawaii).[3] This heavy dependance on ground water as a source of drinking water demands every effort to protect the remaining ground water aquifers from sources of contamination. Once the aquifer is contaminated, methods available to return it to an acceptable level of water quality are not presently economically feasible.[4]

Where geologic and engineering studies indicate that a prospective site is suitable for subsurface injection, this method of hazardous waste disposal should be pursued. Few cases of ground water contamination resulting from subsurface injection operations have been documented. Technological advances and more restrictive waste injection regulations have virtually eliminated the potential sources of contamination which presented problems in the past. Subsurface injection has demonstrated itself to be an effective means of hazardous waste disposal. Regulatory actions that eliminate subsurface injection as a economical means of hazardous waste disposal will adversely effect the quality of ground water either directly or indirectly.

CHAPTER III

DETERMINING THE AREA OF REVIEW FOR INDUSTRIAL WASTE DISPOSAL WELLS

Introduction

During the course of the past four decades disposal of hazardous wastes by means of subsurface injection has emerged as an acceptable alternative to surface disposal methods. At present, subsurface injection is conducted at more than 300 industrial waste disposal wells located at several geologically favorable sites throughout the country. The largest concentration of industrial waste disposal wells is along the Gulf Coast of Texas. Figure (7). The majority of the wells inject waste into zones located below ground water sources of drinking water at depths between 3000 and 7500 feet. The disposal wells are designed to inject into sedimentary formations, approximately 62% of which are sand formations and 34% of which are limestone dolomite.[5] The sedimentary basins which provide deep reception formations containing brine may also contain shallower formations saturated with ground water suitable for drinking. Since most industrial sites are located within or near densely populated areas which may rely heavily upon undergroundd sources of drinking water, precautions must be taken to ensure that

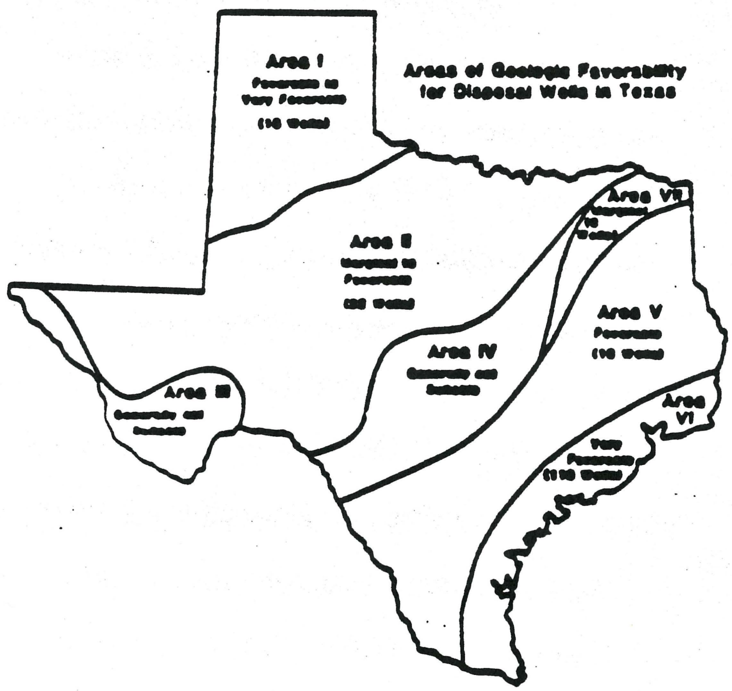


FIGURE 7. Location of waste disposal wells in Texas (From Kent[1])

the waste injection operations do not contaminate the overlying formations containing drinking water.

In compliance with the Safe Drinking Water Act,[6] The Environmental Protection Agency (EPA) has developed minimun requirements for state operated programs designed to regulate the subsurface disposal of industrial waste by injection. This effort is designed to protect underground sources of drinking water from endangerment resulting from underground injection operations. The technical criteria and standards for use by the states in the developement and implementation of their state Underground Injection Control (UIC) Programs were promulgated by the Federal Register on 24 June 1980.[7] Texas was the first state to have an injection well regulatory program and to a large extent the Federal UIC Program was patterned after the Texas guidelines. The Texas Department of Water Resources (TDWR) recently promulgated the Texas UIC program.[8] The program establishes the standards and technical criteria which will govern subsurface disposal of industrial waste in Texas. Appendix A discusses the standards and criteria establishes by the EPA and TDWR.

Several potential sources of groundwater contamination may develop during the life of an injection operation. Potential sources include: 1) failure of th injection well, 2) faults or fractured confining zone, a

3) upward migration of wastes via the abandoned well bores which penetrate the prospective injection zone. An adequate hydrogeologic survey should eliminate the possibility of injecting into excessively faulted zones and/or zones with fractured confining rock. Proper design, installation, maintainance and monitoring of the injection well will virtually eliminate the injector as a source of contamination. The potential for upward migration of waste via the abandoned well bores however, requires further investigation.

This report reviews the criteria which apply to contamination which may result from the migration of native formation fluid and/or injected waste up the abandoned well bore. A procedure is presented to determine which abandoned wells should be reviewed to determine if corrective action is necessary to prevent the contamination of ground water sources of drinking water which may result from upward migration in the abandoned well bore. The procedure is readily applicable in the Gulf Coast Area and can be adapted to other areas as required.

Criteria Which Apply to Abandoned Wells

Defining the Area of Review

The EPA and TDWR have promulgated regulations defining the area of review for an injection well or a group of wells.[7,8] The EPA defines the area of review to be the zone of endangered influence or a radius of 1/4 mile which ever is less. Where the zone of endangered influence is the area outlined by a radial sweep around an injection well, field or project where in the pressures in the injection zone may cause the migration of the injected and/or formation fluid into an underground source of drinking water. The computation of the zone of endangered influence may be based on appropriate equations for pressure calculations and/or models and shall be determined for the life of the injection well system. The TDWR defines the area of review for industrial waste disposal wells as a radius of 2½ miles or an area of lesser radius if so determined by the TDWR. The minimun area of review allowed by the TDWR shall not be less than a 1/4 mile radial distance from the injection well.

References (9) and (10) indicate that the TDWR utilized a formation pressure increase tolerance of .01 or .015 psi/ft at well depth to calculate the pressure resistance in an unplugged abandoned wells. If the formation pressure does not exceed the pressure increase tolerance at a given abandoned well then the area of review may be reduced to exclude that well. The tolerance does not consider the characteristics of the fluid which occupies the abandoned well bore.

Significance of the Area of Review

The significance of the area of review is that the regulations require wells within the area of review, which are not adequately plugged and which as a result of injection operations may cause contamination of subsurface sources of drinking water, to receive corrective action adequate to prevent such contaminaton as a condition of the underground injection operating permit.

The required corrective action is usually the plugging of the abandoned well with cement. Since plugging wells can represent an extensive capital investment, an adequate definition of the area of review becomes an important economic factor which must be considered when the waste injection feasibility study is conducted. If area was fully developed as a result of oil and gas exploration the area defined by a 2½ mile radius would contain more than 300 wells. The cost of locating and plugging that number of wells would be prohibitive.

The Texas UIC regulations[8] require the subsurface disposal well permit applicant to submit a technical report with the application for permit. The information required in the technical report that relates to the area of review includes:

1) A map indicating the location of the proposed injection well and the applicable area of review. Within the area of review, the map must show th

number, or name and location of all producing wells, dry holes, surface bodies of water, springs, mines, quarries, water wells and other pertinent surface features including residences and roads;

2) A tabulation of reasonably available data on all wells within ½ mile of the injection well and all wells within the area of review which penetrate to within 300 feet of the injection zone. The data shall include a description of the type, construction date drilled, location depth, record of plugging and/or completion, and other information of each well as required;

3) Maps and cross-sections indicating the general vertical and lateral limits of those aquifers within the area of review that contain water with less than 3,000 mg/l Total Dissolved Solids (TDS) and those that contain water with less than 10,000 mg/l TDS, their positions relative to the injection formation and the direction of water movement, where known, in each fresh water aquifer which may be affected by the proposed injection.

The cost of obtaining and preparing the above required information could represent a significant percentage of the initial costs associated with the proposed subsurface waste disposal well. Thus the magnitude of the effort required to prepare the permit application and technical report is controlled to a large degree by the determined area of review.

Theoretical Description of the Pressures Acting at the Abandoned Well Bore

Discussion

The vast majority of the artificial penetrations which intersect potential injection aquifers are the result of oil and gas exploration and developement. Therefore, it is logical to conclude that a means of adequately defining the area of review may lie in an understanding of the principals and practices which govern drilling and well completion operations.

The rotary drilling method is predominately utilized in the drilling of oil and gas exploration and development wells. This drilling method is dependant upon the use of a drilling fluid (mud) which performs several functions which are vital to the method. Appendix B provides a brief discussion of the importance of drilling fluid to the rotary drilling method. Upon completion of the drilling operation if the well is not completed for production, the drill string and bit are removed from the well bore. Drilling mud will remain in the well bore. Since no means of escape exists, provided lost circulation zones were not encountered, the drilling mud used to drill the well will remain in the well bore indefinately.

Important Drilling Mud Characteristics

One of the primary functions of the drilling mud is the removal of bit cuttings during the drilling operation. The mud must remove the cuttings from beneath the bit, transport them up the well bore-drill pipe annulus and release them at the surface. During periods of suspended circulation, the primary mud property which acts to suspend the cuttings in the static mud column is the mud gel strength. The gel strength develops with time as the mud column remains quiescent. Since the bouyant force of a static fluid increases with density, drilling fluids of higher density are also capable of suspending cuttings during periods of non-circulation. The density of the mud also accomplishes another important function, that of controlling encountered formation pressures by providing a static mud column which is capable of exerting sufficient pressure to prevent the inflow of formation fluids into the well bore.

Pressures at the Well Bore

An abandoned well bore can be considered to exist in a static state. For a static state to exist the force which act on the mud column must balance. Figure 1 represents a vertical force diagram of the static mud column i an abandoned well bore. The equation for the force balance takes the following form,

$$w + 2\pi r_w h\ GS = P_f\ \pi r_w^2 - P_t\ \pi r_w^2 \qquad (1\text{-}1)$$

where $w = \pi r_w^2 \gamma h$

Simplifying the force balance results in the following pressure equation,

$$P_f = \gamma h + \frac{4hGS}{D} \qquad (3\text{-}1)$$

Pressure Generated by the Static Mud Column

The hydrostatic law of variance of pressure can be written in the form,

$$P = \gamma h \qquad (3\text{-}2)$$

Where: h denotes the height of the liquid column, ft P denotes the pressure at the base of the tical liquid column of height h. lbs/ft^2

γ denotes the specific weight, lbs/ft^3

Equation 3-2 can be transformed into the following usable field equation:

$$P_s = 0.052\ \rho h \qquad (3\text{-}3)$$

Where: the contant 0.052 has the units $gal/ft\text{-}in^2$

ρ denotes the density of drilling mud, lbs/gal

h denotes the height of

static mud column, ft

Ps denotes the static mud column pressure, psi

<u>Pressure Required to Break the Gel Strength of the Static Mud Column and Initiate Flow</u>

Most oil and gas wells are drilled utilizing water base drilling fluids. When these fluids remain in a quiescent state a gel structure developes. The strength of this structure is important since the formation pressure would have to increase sufficiently to shear this structure before the mud in the abandoned well will flow freely. Melrose, et al[11] defined the pressure gradient required to rupture the gel strength and initiate flow in a horizontal pipe as:

$$\frac{\Delta P}{h} = \frac{4GS}{D} \quad (3\text{-}4)$$

Equation 3-4 can be converted to the following usable field equation:

$$Pg = 3.33 \times 10^{-3} \quad \frac{Gsh}{D} \quad (3\text{-}5)$$

Where: The constant $3.33X10^{-3}$ has the units ft/i

h denotes the height of the static mud column, ft

GS denotes the gel strength of the drilling mud, lbs/100 ft^2 (Gel strength pressure, Psi)

D denotes the diameter of the abandoned

well bore, in P_g denotes the pressure required to break the gel structure and initiate flow in a horizontal pipe system where gravity effects are negligible

Formation Pressure Rise During Injection

The well life formation pressure (P_f) which results at a radial distance r from the injection well at time t after the start of injection of a small and constant compressible fluid at a constant rate Q throughout the life of the well into an infinite, isotropic, homogeneous, horizontal reservoir of uniform thickness and porosity is well approximated by,[12].

$$P_f(r, t) = P_i - \frac{Q u B}{4 \pi K h} \; Ei \left(\frac{-\phi u c r^2}{4 k t} \right) \qquad (3\text{-}6)$$

Appendix C provides a definition of the terms of equation 3-6 and demonstrates the derivation of the equation from the diffusivity equation.

Pressure Theory Summary

The area of review may theoretically be defined as the radial distance from an injection well where in:

The formation pressure is greater than the static mud column pressure + the gel strength pressure of the static mud column which occupies the abandoned well bore

$$P_f > P_s + P_g \qquad (3\text{-}7)$$

Field Procedure for Determining the Area of Review

Introduction

This section of the report promulgates a general procedure which can be utilized to determine the area of review for a proposed subsurface injection disposal operation. The procedure employs the developed theory to determine which abandoned wells must be reviewed to determine if corrective action is required. The corrective action is required to prevent the contamination of underground sources of drinking water which could result from the migration of waste and/or formation fluid up the abandoned well bore. Application of the procedure during the initial planning stages of a proposed injection operation could play an important role in the decision making process. The variations and options provided by the procedure will allow planners the flexibility of varing the injection rates, well locations and other pertinent factors to insure that the required injection operation can be accomplished without the expenditure of funds to physically locate and/or correct abandoned wells unnecessarily.

Assumptions

1.) The static mud column extends to the surface and is uniform in density.

2.) Abandoned well bore diameters used in calculations are equal to the bit diameter plus two inches where bit refers to that used to drill the hole at the depth of the injection formation.

3.) The gel strength applied to all wells is 20 lbs/100 Ft^2

4.) Injection pressures will not exceed the fracture pressure of the injection formation.

5.) Known abandoned wells for which no data are available will be assigned the minimum mud density and the largest bit diameter noted for all wells within a 2½ mile radius of the injector.

6.) None of the abandoned wells were completed and produced.

7.) All pressures are calculated at the top of the injection formation.

8.) All abandoned wells were drilled with water base muds. (fresh water, salt water, oil-in-water emulsions and surfactant muds).

9.) None of the abandoned wells were plugged.

Justification of Assumptions

1.) Upon entering some abandoned wells it has been noted that segregation of the mud components doe occur with time. A sedimentary process apparently occurs to some degree within the static mud column. Data describing the degree to which sedimentation occurs is not readily available since the phenomenon has received little attention. If segregation of the mud column occurs the mud density will increase with depth. The actual characteristics of the density gradient is not known since it would vary with the mud type, composition and the characteristics of the formation drilled. Since the mud has no means of escape from the well bore the assumption that the mud column has a constant density with depths should result in the calculation of a static mud colum pressure at the depths of concern which varies little, if at all, from the actual pressure. Here again the gel structure would be expected to increase with depth because of the deposition of the gel producing particles at the lower portion of the well bore. The assumption of uniform mud consistency provides the only means of calculating the gel strength pressure since the variations of gel strength with mud segregation in abandoned wells are not known.

2.) The gel strength pressure (Pg) is inversely proportioned to the well bore diameter, therefore to compensate for the larger surface casing the effective diameter of the abandoned well bore will be the bit diameter used to drill the hole at the depth of the injection formation plus two inches.

3.) The justification for selecting 20 lbs/100 Ft^2 as the expected minimun gel strength for all water base muds is discussed in Appendix D.

6.) If an abandoned well was completed and produced the fluid occupying the well bore will be a ligh' fluid without gel strength and the procedure described here would not apply.

8.) Because of the lack of gel strength associated with oil-base, air and gas drilling fluids wells drilled or completed with these fluids should be evaluated by alternate procedures.

9.) Considering all wells to be unplugged allows the pressure calculations to be conducted on the sta tic mud column in each abandoned well bore in an equitable manner for all wells.

Example

Appendix E is an example which correlates with th procedural steps presented below. The example represents a two well injection system which is injecting into a zor with characteristics selected to emphasize the procedure. The abandoned wells represent an actual field orientatio and the mud densities and bit sizes utilized were obtain from the well logs for the various wells.

Step 1

The first step in the procedure is obtaining the information required to calculate the pressures. Table 2 lists the subsurface information required and the means by which it can be evaluated. An effort to attain well logs for all abandoned wells within a 2½ mile radius of the proposed injection well or wells should ensue. The appropriate state regulatory agency for oil and gas exploration should be contacted for assistance in obtaining well logs or a commercial log library can be contacted.

Step 2

Upon completion of a thorough investigation to locate all abandoned wells within the 2½ mile radius of the injectors, the abandoned well locations should be accurately indicated on a suitable map. An appropriate grid system which indicates the distance, in feet between the abandoned wells should then be superimposed over the map. The grid system provides a means by which the relative distance between the abandoned wells and the injection wells can be determined so that the pressures resulting from the injection operation can be evaluated at each abandoned well.

TABLE 2.

SUBSURFACE INFORMATION REQUIRED FOR PRESSURE CALCULATIONS

PRESSURE CALCULATED	INFORMATION DESIRED	METHODS AVAILABLE FOR EVALUATION
Formation	Porosity	Core analysis, electric, soni[c] and radioactive logs
	Permeability	core analysis, buildup, drawdow[n] or injectivity tests or electric logs
	Formation fluid pressure	Drill stem test, hydrostatic pressure gradient, pressure bomb
	Formation thickness	electric logs, sonic logs, radioactive logs
	Formation depth	electric, sonic and radioactive logs
Static mud column	Mud density	well log headers
	Formation depth	(same as above)
Gel strength	Bit size	well log headers
	Formation depth	(same as above)

Step 3

Utilizing the information gathered in step one, the formation, static mud column, and gel strength pressures are calculated. The formation pressure calculated must represent the injection formation pressure at the end of the stated life of the injection well system. A computer program INJWEL (Appendix F) was developed to calculate the required pressures. Use of the program is demonstrated in the example contained in Appendix E. The program calculates the formation pressure, static mud column, and gel strength pressures up to a radial distance of 13,000 feet (approx. 2½ miles) from the injector. The program also generates an X-Y Plot of the formation, static mud column, and static mud column + gel strength pressures as a function of the radial distance from the injection well. The x-y Plot graphically approximates the area of review by indicating the radial distance from the injector where the static mud column + gel strength pressure exceed the formation pressure. Since most waste injection operations utilize more than one injection well the program can be used in these instances by assuming that the combined flow rates of all injectors is input into one well. Since the wells are usually located relatively close together this assumption should provide a realistic approximation of the area of review. The program is designed to calculate the formation pressure utilizing an input flow rate or by determining a maximum allowable flow rate utilizing an input formation fractur pressure.

The static mud column pressure calculated by INJWEL depends on the mud density.

$$P_s = 0.052\rho h \tag{3-3}$$

Since the mud density varies with each abandoned well, the static mud column pressure will also vary. To define properly the area of review it is necessary to take the extreme case where P_s is a minimun. Therefore the density to be utilized in the static mud column pressure calculation must be the lowest density recorded in the abandoned wells within a 2½ mile radius of the injectors. Equation 3-3 can be modified to yield the appropriate equation:

$$P_s = 0.052\ \rho_{min}\ h \tag{3-8}$$

The gel strength presure calculated by INJWEL is inversely proportional to the diameter of the abandoned well. Since the diameters of the abandoned wells vary, proper definition of the area of review requires the use of the minimun gel strength pressure calculated in the abandoned wells located in the 2½ mile radius of the injectors. This minimun theoretically will occur in the abandoned well drilled with the largest bit size at the injection formation depth. Equation 3-5 can be modified t yield the appropriate equation:

$$P_g = 3.33 \times 10^{-3} \frac{Gsh}{D_{max}} \quad (3\text{-}9)$$

Where: D may denote the largest bit diameter at the injection formation depth plus two inches.

Step 4

The information obtained in step two is utilized in this step to determine the formation pressure at each of the abandoned wells for the specified time period. The formation pressure is calculated by utilizing a computer program PRES (Appendix (G)) which has undergone some FORTRAN modification from the original program developed by Carter.[13] The program determines the formation pressure at each abandoned well at specified time periods. For use in calculating the area of review the time must equal the life of the injection well or wells. Although an average injection rate would suffice, the program is capable of determining the formation pressure at a specified time for wells injecting at varing rates. The use of PRES is demonstrated in the example contained in Appendix E. In addition to calculating the pressures at the abandoned wells PRES also generates an X-Y Plot which locates the injectors and the abandoned wells on an appropriate grid system. The x-y Plot also contains an isobar which represents the static mud column + gel strength pres-pressure calculated by INJWEL in step three. This isobar c fines the area of review. Inside the area encompassed by t